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Space Surveillance Network (SSN) Optical Augmentation (SOA)

AFTER INITIATIVE REPORT

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1. This Kenney Battlelab After Initiative Report is provided for your information and/or action as appropriate.

2. Major Walter Andress was the project officer for this Space Battlelab initiative. Because of his departure from the Space Battlelab, please direct all questions and comments to 1st Lt Robin Schendzielos, DSN 560-9512 or commercial (719) 567-9512. E-mail: robin.schendzielos@swc.schriever.af.mil.

Robert L. Bivins

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Attachment:
SOA After Initiative Report

EXECUTIVE SUMMARY

Space Surveillance Network (SSN) Optical Augmentation (SOA)

Surveillance of space is essential for effective space control. Surveillance of space provides space situational awareness which is the foundation of space superiority. The SSN has deep space coverage and capacity limitations in deep space surveillance. Too many objects receive inadequate tracking and the problem will only get worse as the number of objects on-orbit increases. The purpose of this initiative was to demonstrate the potential for remote, autonomous collection and reporting of metric data to augment the optical deep space tracking capabilities of the SSN. The demonstration used low cost, commercial off-the-shelf technology to increase the capacity and performance of the SSN by off-loading the routine tasking and observation burden from more capable telescopes.

The Air Force Research Laboratory/DEBI (AFRL) submitted the SOA concept to the Space Battlelab. The Space Battlelab's General Officer Advisory Group (GOAG) approved the initiative for execution with $590,000 on 11 September 1997.

The Space Battlelab conducted the demonstration at the 18th Space Surveillance Squadron, Edwards AFB, CA from 28 July through 14 August 1998. During the demonstration, AFRL was responsible for the telescope control system and for performing data reduction. The Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) was responsible for object scheduling, a weather protection system, and communications between Socorro, NM and Edwards AFB.

The demonstration met its objectives:

Objective 1: SOA successfully demonstrated remote, autonomous collection and reporting of metric data on deep space objects. During the demonstration period, the system produced nearly 6,000 metric observations without any human intervention.

Objective 2: SOA demonstrated the value added of geographically dispersed sensors to the SSN. SOA collected data when the Socorro and Maui Ground-based Electro-Optical Deep Space Surveillance (GEODSS) sites were out of operations due to bad weather. However, the observations were not reported into the operational system at Cheyenne Mountain Air Station (CMAS), therefore the impact on SSN performance of dispersed sensors was not directly measured.

The throughput of the system, if operated in a mode consistent with what was learned during this test, is between 40 and 45 satellite attempts per hour. SOA's acquisition rate, throughput, and accuracy are similar to GEODSS. SOA's less capable telescopes are still able to see 70% of deep space objects. SOA is a low-cost ($5-7M for three sites based upon an independent cost estimate from Aerospace Corporation) augmentation to the SSN with an estimated O&M cost/object of $6 compared to $38 for baseline GEODSS and $15 dollars for refurbished GEODSS.

One of the benefits of SOA is its use of astrometry, where the position of the stars determines the position of the satellites. Not only is the accuracy of the observations (up to 5 times better than GEODSS) better than with a system that uses mount encoders, but if multiple satellites appear in the image, the position of all of the satellites can be determined simultaneously. The current GEODSS system does not use astrometry.

In general, the system configuration used for the SOA demonstration was successful. The availability and operational status of the autonomous SOA telescope and data analysis system was high. However, there are two hardware changes identified during the demonstration that would substantially improve the system performance: expand the telescope FOV and minimize the telescope mount limitations.

The Space Battlelab conducted SOA to demonstrate an innovative low-cost approach to meet some of Air Force Space Command's (AFSPC) space surveillance requirements. Based on this successful demonstration, the Space Battlelab recommends AFSPC fund the acquisition of three upgraded SOA-like systems with 1-degree field-of-view (FOV) telescope and tracking mounts in FY02. HQ AFSPC should deploy the three systems to ensure redundant coverage of deep space. In addition to the coverage improvements, the SSN capacity would also improve. Although the total capacity shortfall would still exist, three-telescope augmentation should allow the SSN to meet the GEODSS ORD requirement to track all deep space objects once every three days. In addition, SOA should significantly reduce the number of objects on the attention and lost list. At the time of this After Initiative Report, HQ AFSPC/DRC is building the FY02 POM input to acquire SOA-like systems.

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1. DEMONSTRATION MISSION STATEMENT

A. Purpose

The purpose of the SOA initiative was to demonstrate remote, autonomous collection, and reporting of metric data to augment the optical deep space tracking capabilities of the Space Surveillance Network (SSN). The demonstration used low cost, commercial off-the-shelf technology to increase the capacity and performance of the existing network of sensors by off-loading the routine tasking and observation burden from more capable telescopes. SOA gives flexibility by freeing these telescopes to do more of the difficult missions of search and space object identification (SOI), for which they are designed, or more metrics as the need varies.

1. Background

Surveillance of space is essential for effective space control. Surveillance of space provides space situational awareness which is the foundation of space superiority. The Ground-based Electro-Optical Deep space Surveillance System (GEODSS) Operational Requirements Document dated 20 Nov 96 defined the tracking requirements:

As a system (GEODSS), the threshold for collecting metric data for space catalog maintenance of satellite orbital parameters is one track per deep-space object every three days. This frequency of tracking is an average required to maintain element sets on non-maneuvering deep space objects to an accuracy permitting subsequent reacquisition. The objective is one track per deep space object every day.

As a system (GEODSS), the threshold for collecting metric data for maneuver and conjunction detection is one track for every maneuverable object per day. This tracking frequency ensures detection of a maneuvering satellite before it moves so far from its assumed position it becomes lost. The objective is two tracks for every maneuverable object every day.

Metric data is position, velocity vector and time parameters used to determine orbit ephemeris. The optical network consists of GEODSS sites at Socorro, NM, Maui, HI and Diego Garcia, each with three 1 meter telescopes and Ebsicon cameras, and the Transportable Optical System (TOS) in Moron, Spain with a single 24 inch telescope and CCD camera.

The optical network, while able to perform its mission, is limited in its capacity and coverage. Today the 1st Command and Control Squadron (1 CACS) tasks the network to track over 2,000 objects in deep space. On average, the optical network tracks objects once every three days. However, the SSN has not tracked approximately 15 percent of cataloged deep space objects in 5 - 30 days and 10 percent in more than 30 days, which are on the lost list. The Optical Network Mission Study (ONMS) sponsored by AFSPC and considered to be the most credible study to date projected that the number of deep space (DS) objects will increase significantly by the year 2005 (see Figure 1). Scheduled SSN sustainment upgrades will not keep pace with this projected increase. In addition, there is little overlap in sensor coverage (see Figure 2) in the European and Asian regions.

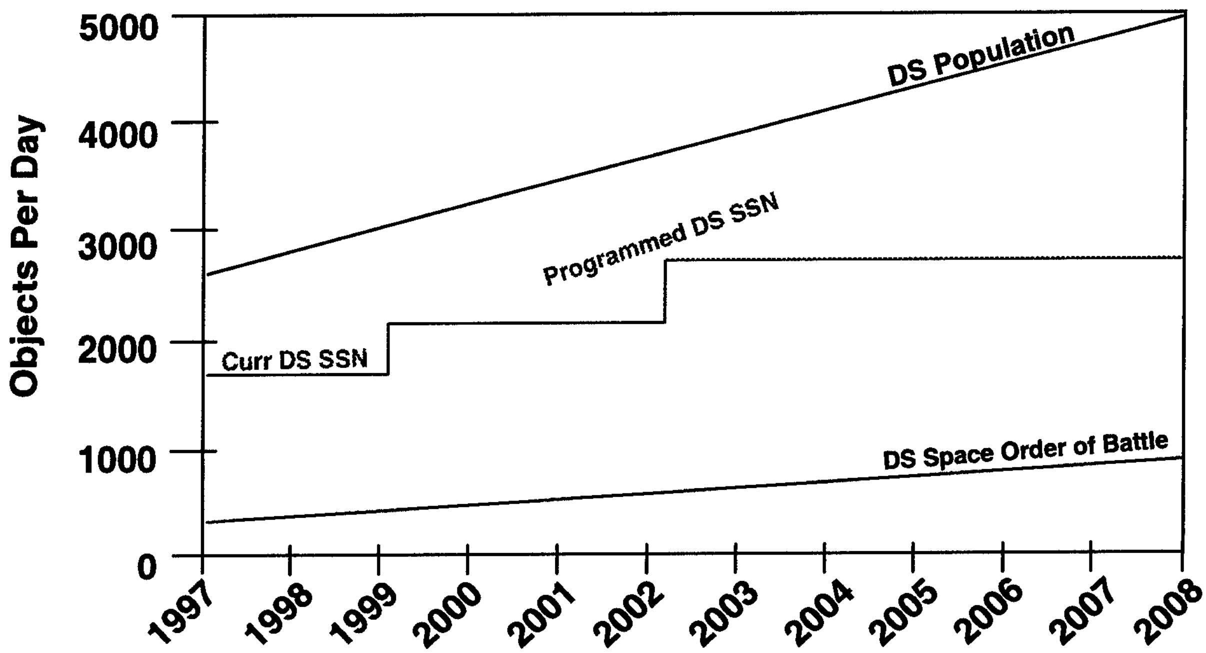


Figure 1 Capacity Shortfalls

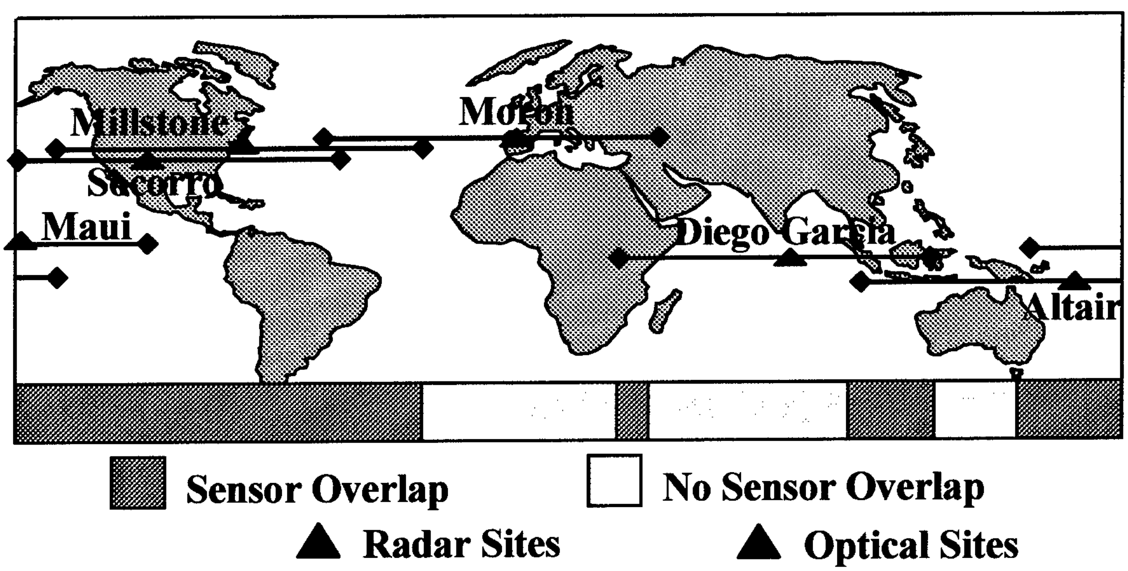


Figure 2 SSN Deep Space Coverage

Cloud coverage sometimes precludes sensor operation and thus affects the performance of the network. Weather at Diego Garcia precludes operation ~50% of the time. Weather at Moron Spain precludes operation ~20% of the time.

The Space Battlelab conducted SOA to demonstrate an innovative low-cost approach to meet some of AFSPC's deep space surveillance requirements.

B. Length of Time

1. Submittal of Battlelab Initiative to Approval

Air Force Research Laboratory (AFRL) /DEBI submitted the SOA concept to the Space Battlelab on 9 June 1997. The Space Battlelab presented the concept to the Battlelab Planning Cell (BPC) on 31 July 1997. The Space Battlelab General Officer Advisory Group (GOAG) approved the SOA concept for detailed planning on 8 August 1997 and for execution on 11 September 1997. The GOAG allocated SOA $440K in FY97 and $150K in FY 98 for the demonstration. The total time from submittal to execution approval was three months.

2. From Approval to Completion

The execution of SOA began on 11 September 1997. The Space Battlelab completed the demonstration on 14 August 1998.

C. Objectives and Measures of Merit

Primary Objective 1 - Demonstrate remote, autonomous collection and reporting of metric data on deep space objects for use by USSPACECOM in the maintenance of the satellite catalog. Measure of merit for collection was the ability of the system to autonomously execute an observation schedule, based on a daily tasking message originating from 1st Command and Control Squadron (1 CACS), by accurately pointing, tracking, observing and correlating observations in a timely manner with a high throughput. Measure of merit for reporting was the ability to report correlated observations to a geographically separated location.

Primary Objective 2 - Demonstrate the value added of geographically dispersed sensors to the SSN. Measure of merit was the ability to improve the quality of the USSPACECOM element set database by decreasing the number of objects on the lost list or increasing the accuracy of the database with more frequent observations during the demonstration.

2. COURSE OF ACTION

A. Overview

The Space Battlelab worked with both AFRL/DEBI and the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) to conduct the demonstration. The Space Battlelab conducted the demonstration at the 18th Space Surveillance Squadron (18 SPSS), Edwards AFB CA. During the demonstration, AFRL was responsible for the telescope control system and data reduction. MIT/LL was responsible for object scheduling, a weather protection system, and communications between Socorro, NM and Edwards AFB.

The nightly operations flow (Figure 3) was as follows:

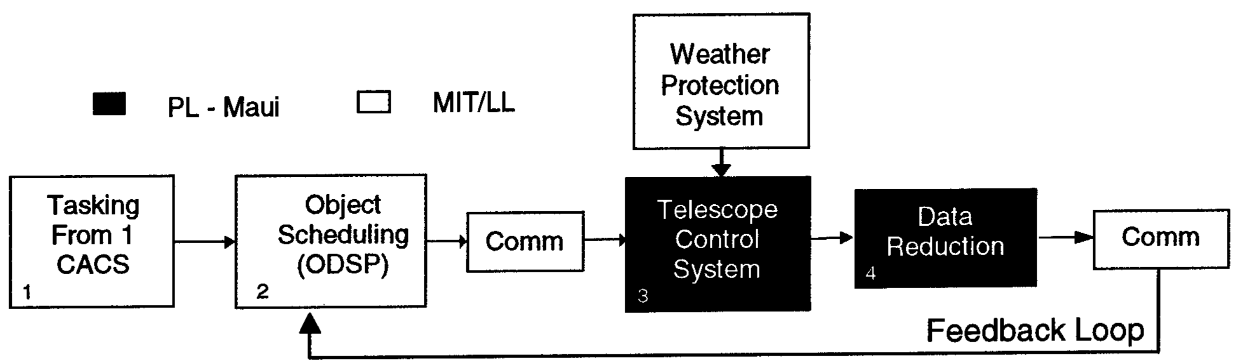


Figure 3 Nightly Operations Flow

1) 1 CACS indirectly tasked the system to collect metric observations. With no direct connections to Cheyenne Mountain Air Station (CMAS), the system took the tasking 1 CACS sent to both the Socorro and Maui GEODSS site and combined them to create the tasking for SOA.

2) The MIT/LL Optical Dynamic Scheduler Prototype (ODSP), residing at the MIT/LL Eastern Test Site (ETS), Socorro, New Mexico, took the combined tasking as input and developed a schedule for metric collections. The feedback loop shown between the telescope and the scheduler allowed the scheduler to know if an individual metric collection was successful. In addition, the telescope indicated if stars were present in the image for a weather exclusion zone program included in ODSP. This program allowed the scheduler to avoid scheduling metrics in regions of the sky that were cloud covered.

3) The telescope control system autonomously (no human in the loop) received specific object tasking and the most recent element set from the ODSP. The telescope control system determined the correct pointing angles for the telescope, pointed the telescope, and initiated the collection of the observation.

4) The system automatically downloaded the resulting frames of data from the charged-coupled device (CCD) camera. The system processed the resulting frame(s) into standard reporting format (B3) for metric observations and sent the observations to the scheduler.

AFRL and MIT/LL each logged and analyzed the results to determine system performance.

B. Detailed System Description

Figure 4 shows a schematic overview of the system.

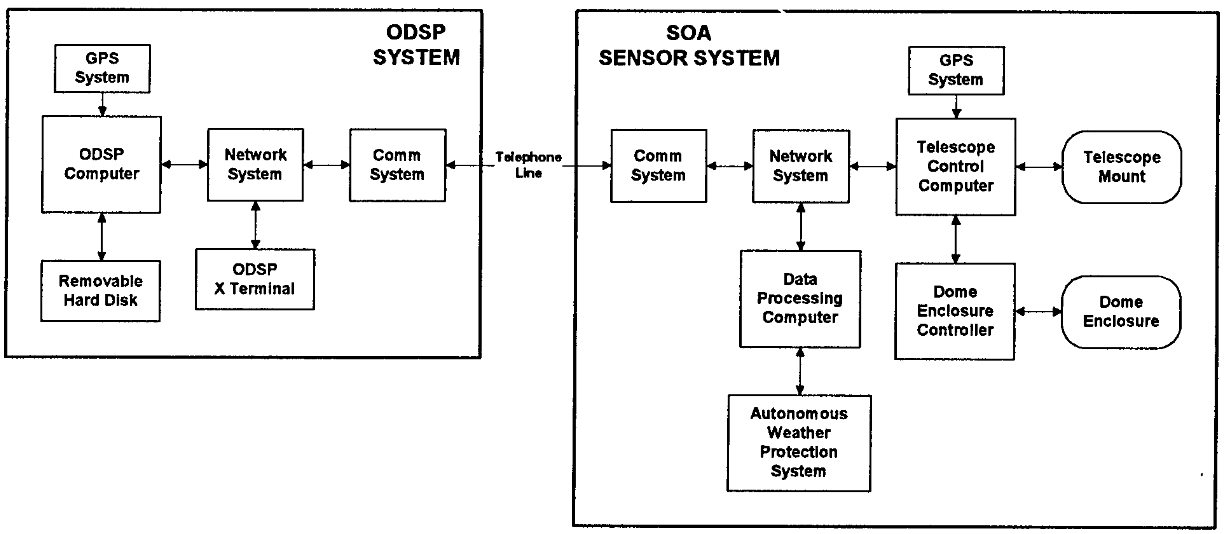


Figure 4 SOA System Overview

1. Optical Dynamic Scheduler Prototype (ODSP)

a. Background

HQ AFSPC has planned for a substantial refurbishment and sustainment program for the GEODSS system. Ultimately, the refurbishment will include replacement of the control computers as well as the aging Ebsicon cameras. The refurbished GEODSS systems will be the primary component of an integrated optical sensor network controlled from a central facility located at Edwards Air Force Base in California. This facility, the Optical Command Control and Communication Facility (OC^3F) at the 18th Space Surveillance Squadron, will provide centralized dynamic scheduling of metric, search, and space object identification (SOI) tasking to all optical sensors in the SSN. Litton/PRC developed the OC^3F software as a major part of the GEODSS Modification Program (GMP). The OC^3F tasks the entire optical network as a single unit and adjusts tasking based on individual sensor capabilities, coverage, operational status, weather and capacity.

In support of the development of the OC^{3}F centralized dynamic scheduler, MIT/LL developed the Optical Dynamic Scheduler Prototype (ODSP). The ODSP is a natural extension of the dynamic scheduler used by the Transportable Optical System (TOS) deployed in Moron, Spain which provides real-time dynamic scheduling for a single optical telescope using multiple scheduling criteria.

b. ODSP Design Overview

The heart of the ODSP is the SKYMAP propagator and memory region. This memory region contains the element sets, physical characteristics, and the geocentric and topocentric positions of each satellite in the deep space object catalog. The SKYMAP propagator maintains the geocentric and topocentric positions and recomputes the position of each object several times a minute.

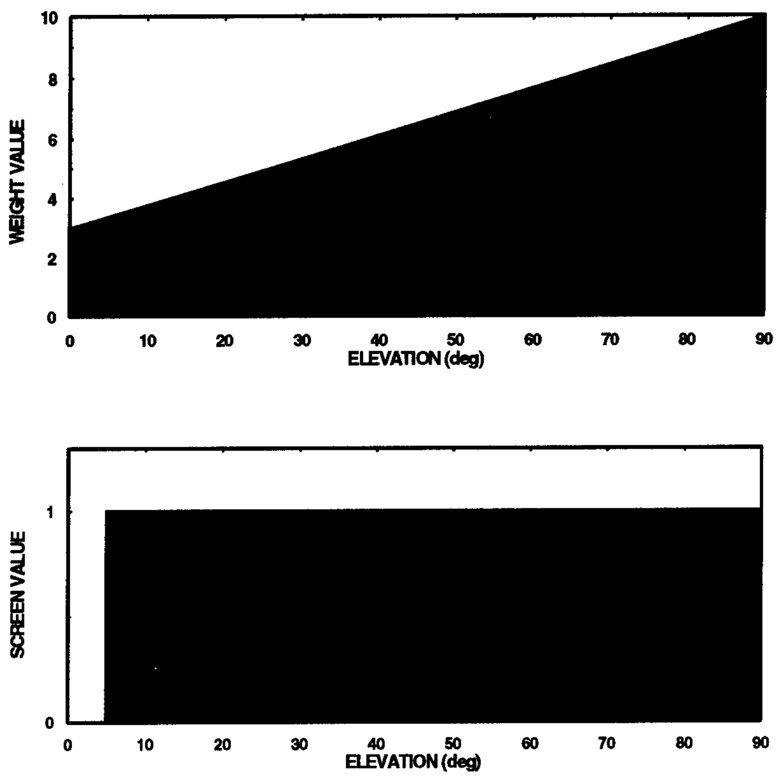


Figure 5 Sample Weighting and Screen Function

For each scheduling request, the ODSP calculates a figure of merit for each tasked satellite. The ODSP then commands the sensor to observe the object with the highest figure of merit.

In Figure 5, we present a simple example of one of the scheduling criteria, satellite elevation. In this example, the scheduler attempts to favor scheduling of satellites at high elevation, when viewing conditions are optimal. However, ODSP never schedules a satellite with an elevation of less than 5° due to the mechanical limitations of the GEODSS mount. For other sensors, different elevation limits can be set. For azimuth/elevation mounts, an upper elevation limit is generally required to avoid the mount singularity at the zenith. The cause of the mount singularity is the inability of the mount to slew over the top; instead, it must slew all the way around to reach the other side. Note that simply returning a weighting function of zero would not be sufficient to guarantee that ODSP would not schedule the object. In general, we can graphically represent each of the scheduling criteria, although the variables represented on the x-axis may vary from criteria to criteria.

As a second example, consider the weighting function for mean anomaly. A common problem with GEODSS operations is that they tend to cause geosynchronous satellites to be observed at approximately the same time of the night. In terms of the orbital elements, it also observes the object at roughly the same mean anomaly each night. Consequently, the GEODSS system clusters the observations it supplies to the Space Control Center along the same limited portion of the satellite orbit. The result is poor sampling of the orbit and a poor orbit determination. To mitigate this problem, the ODSP retains the mean anomalies of the last three tracks on each tasked object. It defines a weighting function, shown in Figure 6. This weighting function prevents scheduling of the object at the same mean anomaly on subsequent tracks and increases sampling of the orbit.

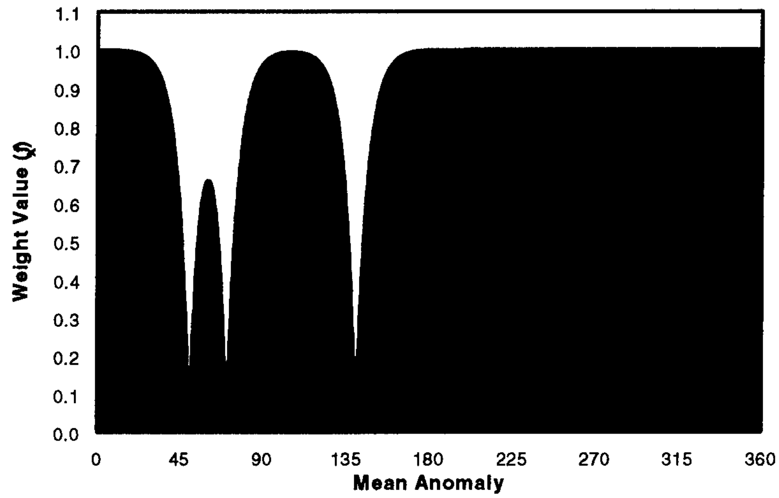


Figure 6 ODSP Mean Anomaly Weight Function

(1) Weather Exclusion Zone Program

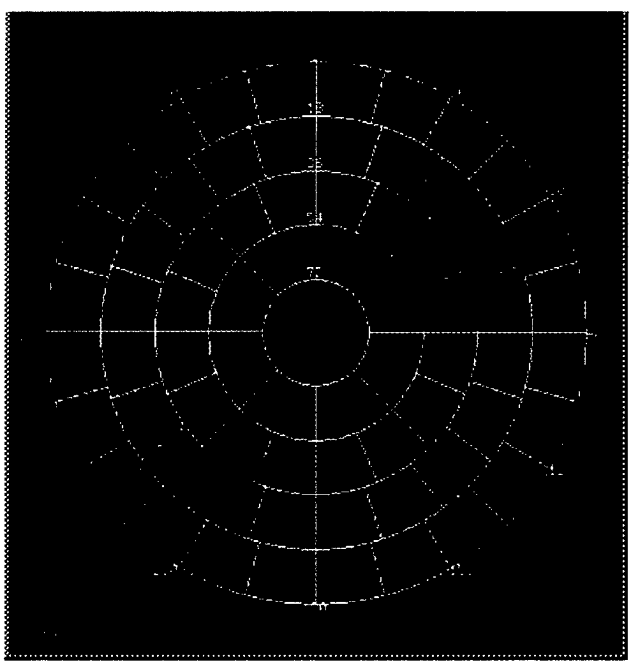


Figure 7 ODSP Exclusion Zone Map.

The ODSP maintains an exclusion zone map for the purposes of scheduling optical sensors under partly cloudy conditions. This map divides the visible hemisphere of sky into 69 regions (see Figure 7). Each of these regions can be marked as excluded by the sensor. Generally, the sensors use this feature to prevent scheduling of satellites within regions of the sky which are unobservable due to clouds, nearby buildings, or other adverse conditions. The centralized scheduler at the OC^{3}F will support exclusion zone maps for each sensor site when the current GEODSS upgrade program is complete. However, there are currently no operational exclusion zone sensors (EZS) at the GEODSS sites.

During the SOA

demonstration, we used an alternative method of maintaining this exclusion zone map using only the SOA telescope itself. With this approach, each time the sensor reported a weather miss on a scheduled metric track, the scheduler set the corresponding zone in the exclusion zone map to cloudy. This prevented the scheduler from giving the sensor a second satellite in the same, probably cloudy, region of the sky and forced it to move to new, potentially clear regions. The scheduler automatically reset the region as clear after approximately 20 minutes. Thus, the sensor itself maintained the exclusion zone map. Potentially, this technique would allow sensors without an EZS systems to populate the exclusion zone map at OC^3F using the existing interface and post-upgrade OC^3F functionality.

c. ODSP Computer Hardware

The ODSP and centralized metric observation correlator described below executed on a Motorola MVME-167 single board computer at ETS (see Figure 8). The single board computer supports both System V Unix and a real-time executive called RTUX. The 68040 microprocessor is its base. For the ODSP system, two single board computers are used. The first serves as the host Unix system and executes the ODSP and correlation processes. The SKYMAP process executed on the second, running the real-time executive RTUX. Near the top of the photograph, one can see the Netblazer dial-on-demand router (left, beneath telephone and Lucent SDD-1910 secure data device (right)).

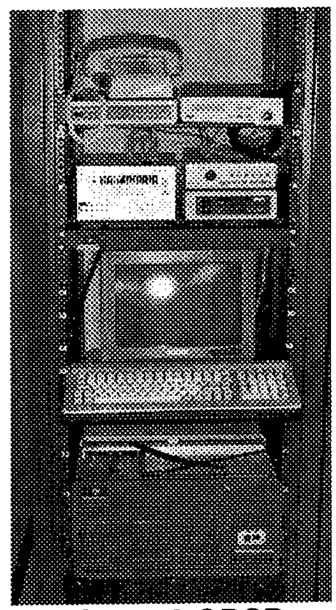


Figure 8 ODSP Computer and Communication Hardware

2. Centralized Metric Observation Correlation Processing

One of the basic functions of the OC^3F is to provide centralized correlation of metric observations for all component sensors using its authoritative database. The ODSP software used for the SOA demonstration also had this functionality, although MIT/LL modified the correlation algorithms to accommodate the 4-5 minute delay in data delivery of the SOA sensor used for the demonstration. ETS made modifications to the algorithm to repropagate (to propagate back) candidate satellites' element sets to the time of the observation. The correlation algorithm used by the ODSP is very similar to the algorithm employed in the TOS. This algorithm makes use of both the satellite angular position and velocity, making it significantly more robust than the observation/object correlation algorithms used in the Space Control Center.

The real-time correlator relies on the same SKYMAP memory region for real-time dynamic scheduling. Upon receipt of metric data from the sensor, the correlator calculates an average angular velocity for the track using the first and last metric observation. Next, SKYMAP identifies all satellites in the immediate area of the observed position at the time of the observation. Finally, in order to correlate the observation with the correct satellite, SKYMAP computes a four dimensional coefficient for each satellite identified. It selects the satellite that produces the largest value that also passes several criteria called screens.

3. Telescope and Dome

The SOA telescope is a 40 cm. (16 in.) f/3.75 Paramount Telescope with an open-framed truss and German equatorial mount provided by Software Bisque[1], Golden, Colorado as shown in Figure 9. A commercial Apogee AP-7 CCD (Figure 10) serves as the imaging sensor for SOA. A two stage thermoelectric cooler complements the CCD camera. Ash Manufacturing[2] provided the 3.2 meter (10 feet 6 inch) dome, including base ring, windscreen, and retractable shutter displayed in Figure 11. Merlin Controls[3] provided the automation for the dome. The dome control system is a clever design, using a Marine battery and recharging solar cell to power the dome shutter and windscreen, eliminating the need for slip rings. A Light Emitting Device and photodiode on the ring motor provide the home position and a single communication connection point for initiating dome opening and closing. The camera shutter triggered a Datum GPS Receiver and Timing interface card, providing accurate timing for the metric data.

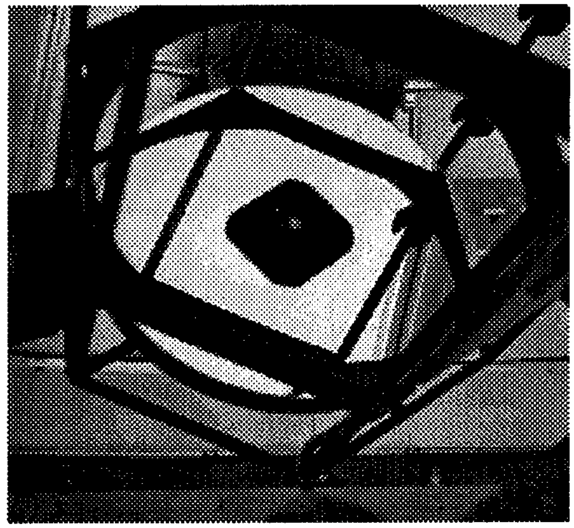


Figure 9 COTS SOA Telescope

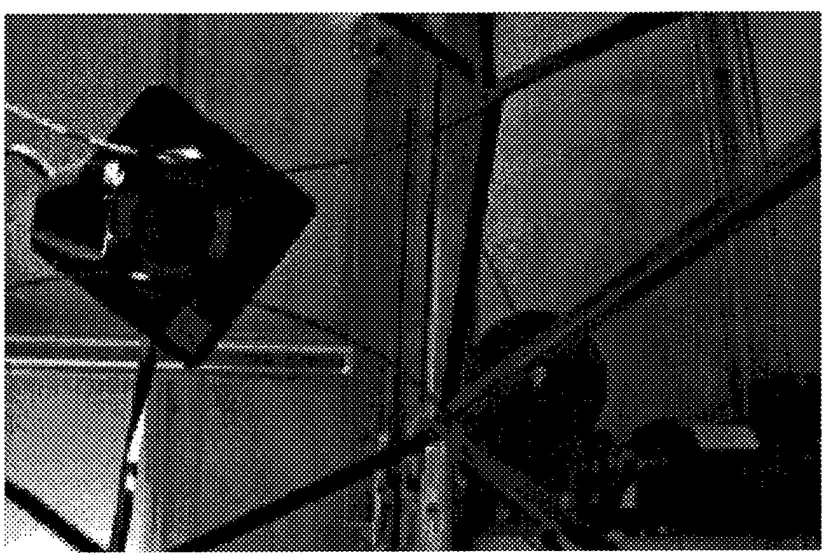


Figure 10 COTS SOA CCD Imaging

The high desert climate at Edwards AFB was a major concern during

[1] Software Bisque, 912 Twelfth Street, Golden, Colorado 80401-1114, Telephone: (800) 843-7599, http://www.bisque.com/.
[2] Ash Manufacturing Company, PO Box 312, Plainfield, IL 60544, Telephone: (815) 436-9403, http://www.ashdome.com/.
[3] Merlin Controls Corporation, PO Box 839, Berthoud, CO 80513, Telephone: (970) 227-9487, http://www.merlin.com/.

planning for SOA. During summer days, the temperature can approach 120 °F, while cooling to 50-60 °F during the night. Since the SOA is autonomous, its control electronics must be running continuously, so electronic overheating during the day was a major concern. In addition, high dome interior temperatures at the start of the night could reduce the effectiveness of the CCD thermoelectric cooler. Consequently, we installed a timer-activated air conditioner in the dome to keep the interior temperature in the 70-80 °F range during the day. The timer turned off the air conditioner before sunset to minimize temperature gradients during the night. An added issue was that large temperature fluctuations might manifest focus changes in the SOA optics. However, this change was not evident during the test period once we fixed the focus adjustment in place.

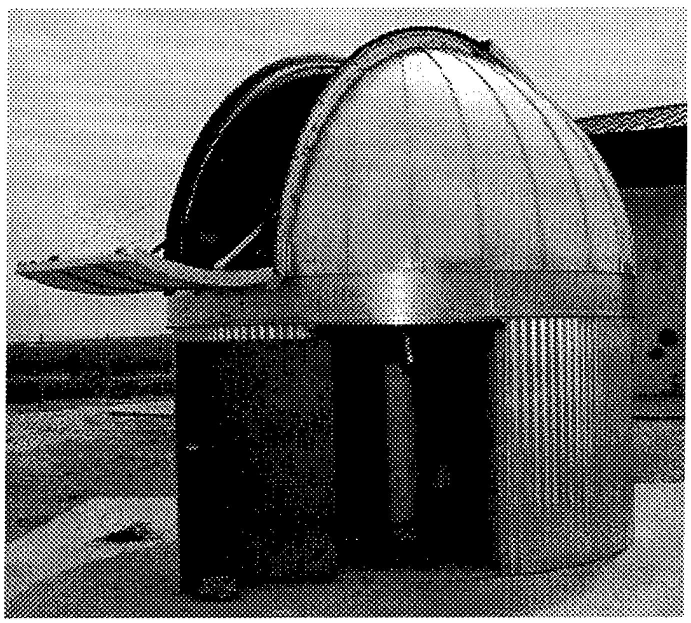


Figure 11 COTS SOA Dome

4. Telescope Control Computer

The telescope control computer is a commercial Pentium-based PC running Windows NT 4.0. The telescope and camera control software is a commercial package called TheSky written by Software Bisque. TheSky package consists of several inter-communicating modules, including:

- TheSky application itself providing telescope and dome monitoring,
- CCDSoft providing CCD camera control,
- Autodome interfacing to the dome control system,
- GPStfp interfacing to the Datum GPS receiver,
- TPoint providing telescope mount modeling for accurate pointing, and
- Orchestrate enabling scripting of telescope pointing, satellite tracking, camera acquisition, and data transfer.

The telescope control computer starts the Orchestrate scripting program on booting, permitting autonomous commanding from the Data Processing Workstation after start-up.

5. Data Processing Workstation (Odin)

The data processing workstation called Odin is a Silicon Graphics Octane UNIX workstation running IRIX 6.4. The data processing workstation communicates with the prototype scheduling computer, ODSP, using TCP protocol through an ITK Ethernet router/dialer and Lucent STU-III encrypting modem. Odin reports metric observations in standard B3 format and receives tasking for the next series of observations from the ODSP system using the OC^3F scheduling command language. Once Odin receives a tasking for the next object from ODSP, it generates an observation script, which it sends to the telescope control computer. The data processing workstation monitors weather and communication status until the telescope control PC transfers an image data file in FITS format using FTP protocol. The data processing workstation then analyzes the FITS image file to determine all stars in the fields as well as detect any satellites present. The detected stars are matched against the nominal positions of catalog stars from the Hubble Guide Star Catalog. From this correlation, the equatorial position, orientation, and scale of the image are determined in mean equator, mean equinox of J2000 for the topocentric location of Edwards AFB, CA. Using this computed transformation, the software converts pixel positions of any detected satellites at shutter open and close to equatorial coordinates. It applies annual (stellar) aberration to the coordinates of the satellite to account for light time travel variations due to the Earth's motion around the Sun. These corrected coordinates are then converted to B3 format and correlated against an on-line database of deep space satellite element sets using correlation software provided by the Space Warfare Center Analysis and Engineering Division (HQ SWC/AE). After correlation, the data processing workstation transmits the tagged metric observations to ODSP along with magnitude estimates.

The Odin data processing system also has two additional responsibilities. First, Odin monitors the time, initiates the nightly observations at the beginning of nautical twilight after sunset, with the Sun 12° below the horizon, and terminates at the end of nautical twilight before sunrise. The start-up sequence includes activating TheSky and supporting applications through an Orchestrate script transmitted to the telescope control PC, which opens the dome and activates the thermoelectric cooler for the CCD camera. In addition, as part of the start-up procedure, Odin opens a TCP connection to the ODSP system and requests tasking for the first 3 objects. The shutdown sequence includes parking the telescope in a nominal position, closing the dome, disconnecting communications with the CCD camera, and finally, rebooting the telescope control PC to compensate for any memory leaks in Windows NT. Odin's second responsibility is to communicate with the weather sensor, Autonomous Weather Protection System (AWPS) and initiate a shutdown sequence if AWPS reports the presence of precipitation or winds exceeding a user-defined wind speed, which was set at 30 mph. If Odin detects inclement weather, it requires 30 minutes of dry weather and 5 minutes of wind speeds below 30 mph. before reinitiating the start-up sequence.

6. Autonomous Weather Protection System (AWPS)

AWPS provides local real-time monitoring of meteorological, environmental and system parameters that could be hazardous to an optical telescope. AWPS primary functions are to monitor meteorological and environmental conditions, monitor the health of the host telescope controlling computer, open and close the telescope enclosure and alert personnel if a hazardous condition exists during observing periods. AWPS in effect replaces a human observer with a machine. Figure 12 shows a block diagram of AWPS.

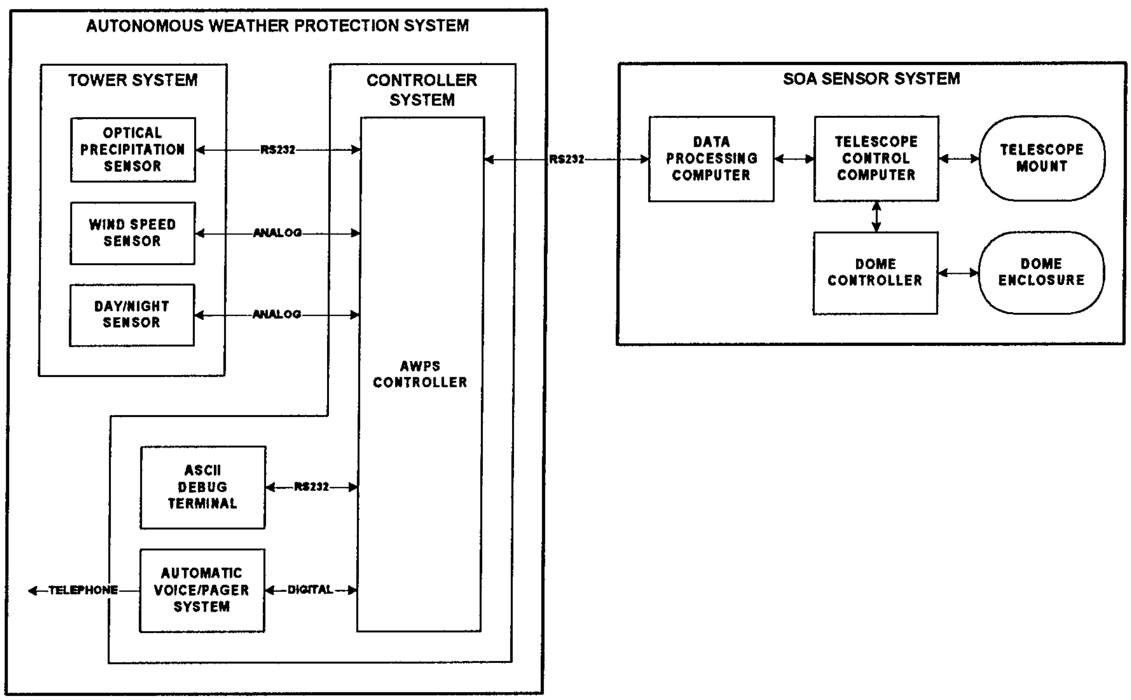


Figure12 AWPS Block Diagram

AWPS consists of two parts; tower system and controller system. The tower system includes the meteorological and environmental sensing equipment, 3-m tower, 1.2-m square base, 2.5-m mast assembly, and support items (see Figure 13). The tower system is co-located with the telescope enclosure to measure local weather conditions and is external to the controller system. For the SOA demonstration, the tower system was about 15 m from the telescope enclosure and 30 m from the controller system. The meteorological and environmental sensing equipment includes an optical precipitation detector, wind speed sensor, and a day/night detector. For the SOA demonstration, we mounted a GPS antenna/receiver on the right mast arm.

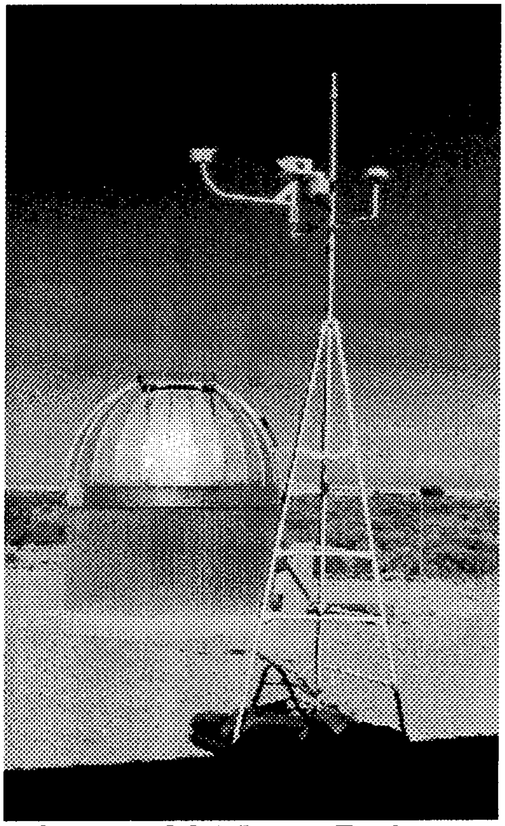


Figure13 SOA Dome Enclosure with AWPS Tower System

The optical precipitation sensor uses precipitation-induced scintillation as the detection method. Falling liquid or frozen precipitation causes beam intensity variations in the infrared light as it passes through the beam. These irregularities, known as scintillation, have characteristic patterns, which the sensor detects and converts to a precipitation rate. The detector has a liquid precipitation range 0.1 to 500 mm/hr (light mist to heavy downpour) and frozen precipitation range of 0.01 to 50 mm/hr (water equivalent) with a time constant of 10 seconds. For the SOA demonstration, the sensor data update rate was once per minute.

The wind speed sensor provides low starting threshold, quick response, and high accuracy with excellent reliability over a wide range of operating conditions. It has an operating dynamic range of 0.44 to 44 m/s (1 to 100 mphs) with a threshold of 0.44 m/s.

The day/night detector senses ambient light using a photodiode detector, which converts light energy into an electrical current. It converts this current into a voltage representing the light energy in foot-candles. A comparator circuit provides a switched output from the sensor corresponding to the sensed daytime or nighttime condition. It reports daytime when the ambient light intensity is above 29 lux (2.7 foot-candles). Nighttime activation occurs when the ambient light intensity falls below 7.5 lux (0.7 foot-candles). In order to calculate visibility conditions, this sensor usually connects to a visibility sensor or transmissometer to indicate whether it should use daytime or nighttime calculations in determining visibility.

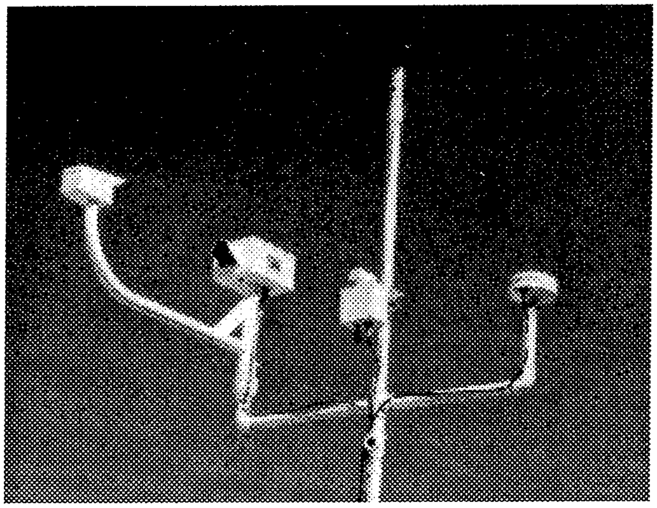


Figure 14 AWPS Mast Assembly

Figure 14 shows a close-up view of the mast assembly. The optical precipitation detector is on the left side, the day/night detector is the lower middle, and the wind speed sensor in at the top middle. The SOA sensor system GPS antenna/receiver head is on the right side.

The controller system includes a MIT/LL designed data acquisition system, an automatic voice/pager dialer, two ASCII display terminals, 120 cm rack, and support items (see Figure 15). The programmable controller consists of a Z180 microprocessor running at 18.432 MHz. The components of the controller fit on a single printed circuit board making it very compact. The controller is C-programmable. Using Dynamic C eliminated the need for in-circuit emulators, logic analyzers, and software simulators. Programming the controller for the SOA demonstration required a modest 400 SLOC (source lines of code).

The SOA Data Processing Computer (DPC) issues an ASCII character "A" every 15 s for heartbeat monitoring by AWPS. AWPS replies with a 70-character ASCII string. The ASCII string contains the present precipitation condition, instantaneous precipitation rate, total precipitation accumulation, wind speed, day or night status, AWPS front-panel controller status, present dome shutter position and AWPS condition ("S" for safe, "U" for unsafe). The front-panel controller ASCII status string included push button switches for enabling or disabling an overall alarm, precipitation alarm, wind speed alarm, daylight condition alarm. Additionally, a front panel switch can enable or disable the voice/pager dialer.

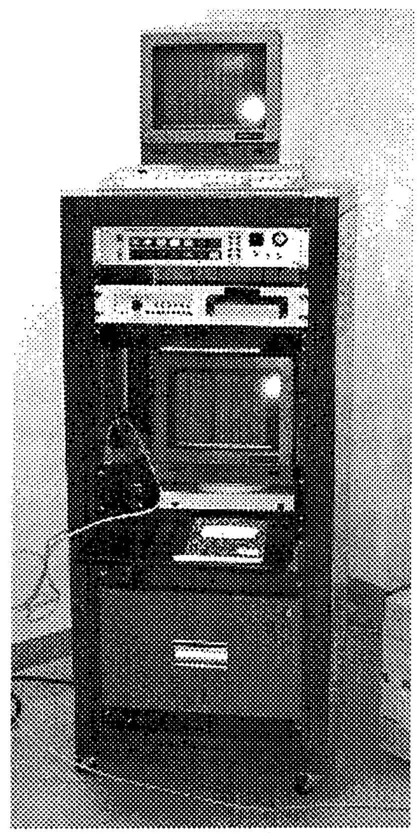


Figure15 AWPS Controller System

In an ideal installation, AWPS has direct control over the dome and can close the telescope shelter without control computer intervention. Normally, this would allow closing the dome if the DPC stopped functioning (as detected by lack of the

"A" heartbeat). Due to interface limitations with the Merlin Controls dome system, AWPS had no direct control over the telescope dome during the SOA demonstration and had to rely on the SOA DPC for telescope safety.

7. Secure Communications

Establishing secure point-to-point communications between the central dynamic scheduler and the sensor sites was a significant challenge. The OC^3F non-GEODSS interface message set and message content is a low bandwidth link. Due to the classification level of some space surveillance data and deep space element sets, the link must provide appropriate security at the SECRET level.[4] Both the SOA demonstration and the future non-GEODSS interface to OC^3F require establishment of TCP/IP connectivity at the ISO-7498 network/service layer.[5] The actual messages that implement remote dynamic scheduling and data delivery for the sensor exchange at the higher, application layer of the interface and function independent of the specific implementation of the network and transport layer. This level of connectivity also support familiar networking tools such as remote login (rlogin), telnet, and file transfer protocol (ftp).

MIT/LL studied several different options to establish secure network connectivity between sensor sites. Table 1 summarizes the options considered. Each method listed implements full network connectivity, but with different levels of performance, initial cost, and operating cost.

The first option uses a Lucent Secure Data Device (SDD) 1910 for data encryption and a dial-on-demand network router. The router converts the network traffic at the site into a serialized data stream using the popular PPP protocol. A SDD-1910 or STU-3 modem can then transmit the traffic to the remote end. When the dial-on-demand router detects network traffic addressed for the remote site, it dials the modem, establishes the remote connection, and transmits the data. The router at the far end receives the data and places it on its local network. The router hangs up the telephone line after a pre-configured duration of inactivity on the link (typically 5-10 minutes). This approach has the lowest initial cost and requires the least infrastructure and lead-time to establish. For these reasons, we chose this method for the SOA demonstration. The availability of secure modems limits the data transfer rate, which is slow in comparison to commercial unsecure modems. Additionally, telephone long distance charges can be substantial.

[4] Even if the sensor was to be scheduled only unclassified objects, the data must be processed and protected at the SECRET level due to the possibility of inadvertently tracking an uncorrelated target (UCT).

[5] The network/service layer is defined in ISO-7498 OSI-RM layered network architecture. This layer equivalent to the interface level established by a PC with dial-up networking under Windows 95/98.

Option	Equipment	Infrastructure	Comments
Dial-on-Demand w/ secure modem	SDD-1910 or STU-III Dial-on-Demand Router	Voice telephone line	Selected for SOA. Current TOS backup capability. Lowest initial cost and infrastructure requirements. High operational cost
Leased Line	KIV-7 or KG Network Router CSU/DSU	Dedicated line	Current TOS capability Typically higher performance and reliability Long lead time for dedicated line install. High operational cost
Network Encryption System (NES)	NES	"Internet" Connection	Highest performance. Allows establishing multi-point secure private network. High initial cost. Uses existing UNCLASS internet connectivity. Low operating cost. Vulnerable to denial-of-service attack. Potential firewall penetration issues.
Dial-on-Demand w/ NES and unsecure modem	COTS modem NES Network Router	Voice telephone line	Allows used of higher speed COTS modems. NES provides data security. High initial cost of NES. High operation cost. Viable operational backup for denial-of-service attack against NES option.

Table 1 Secure Communications Options

The second option uses traditional leased line service and KG-84, KG-194, or KIV-7 serial encryption devices. Network routers serialize the network traffic for the encryption devices and a traditional CSU/DSU interfaces with the leased line. TOS uses this approach. The initial equipment cost is comparable to option one, but the initial installation of a leased line is required. Operational costs are generally lower for a leased line when connect times exceed several hours per day.

The third option is to use pre-existing unclassified Internet connectivity between the sensor site and the central site using Motorola Network Encryption Systems (NES) technology. The NES encrypts data for secure transmission across unsecured wide area networks (WANs) or across a secure WAN such as SIPRNET. The NES is a Type I Controlled Cryptographic Item (CCI), endorsed by the National Security Agency (NSA), under the Commercial COMSEC Endorsement Program (CCEP). The NES can process data up to Top Secret/SCI and uses the same "FIREFLY" algorithm used in the STU-III telephones. The most attractive feature of the NES solution is the use of existing network connectivity, which a host base or other organization usually maintains. However, we must consider several operational issues. First, operational sensors using public networks for communication become vulnerable to "denial-of-service" attacks to the network. Second, local network administrators are generally not required to respond to the operational requirements of the Space Surveillance Network. We can reasonably address both of these problems by combining the NES option with a backup dial-up capability outline in option 4.

The last method is a variation of the same basic scheme outlined in option one. Here, we use NES for data security, but a dial-up connection supplies physical connectivity. The advantage of using the NES as the encryption device instead of the SDD-1910 in option 1 is that now the modem is on the "black" or unclassified side. Now, a high performance COTS modem can be used, improving both bandwidth and noise immunity. The initial hardware is relatively expensive compared to option one. This architecture offers a viable secondary capability to augment the NES solution above should the public network be down or subjected to a denial-of-service attack.

Figure 16 shows the dial-on-demand system integrated for the SOA demonstration period. The technical solution provided on-demand network connectivity between the ODSP and SOA sensor at a bandwidth of 14400 baud. During the integration period, we discovered the vendor had discontinued the originally specified NEC Dr. Bond router and we had to identify, evaluate, and integrate a new network router with dial-on-demand for the demonstration. We ultimately selected the Netblazer LS 2-PT manufactured by ITK International. The Netblazer is ideal for the application as it supports both dial-up and dedicated line, and can use dial-up as backup support for the leased line.

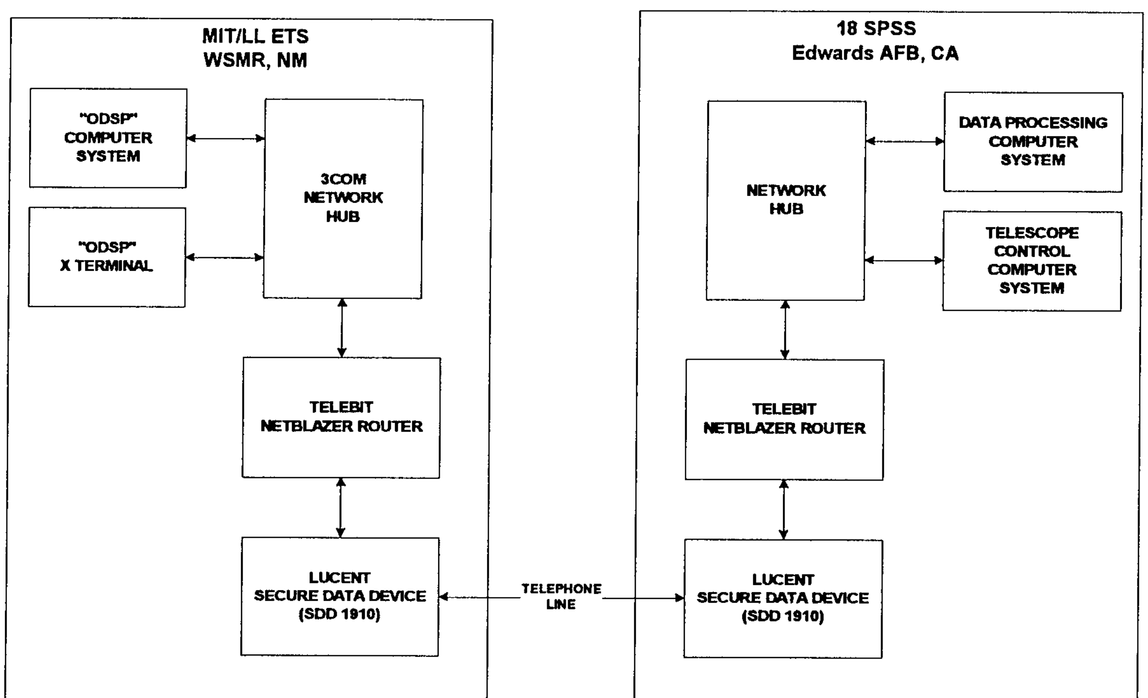


Figure 16 Block Diagram of SOA Communications System

3. RESULTS

A. Objective Satisfaction

Objective 1: SOA successfully demonstrated remote, autonomous collection and reporting of metric data on deep space objects. During the demonstration period of 28

July through 14 August 1998 the SOA system produced nearly 6,000 metric observation without any human intervention at Edwards AFB. SOA reported the data in proper format to the ETS. Unfortunately, the time required (~ 6 months) to gain approval for transmission of the observations into CMAS precluded operational reporting of the data.

Objective 2: SOA demonstrated the value added of geographically dispersed sensors to the SSN. Because ODSP could not report the observations collected at Edwards AFB to 1 CACS and CMAS, we could not directly measure the impact to dispersed sensors. However, during the 18 day demonstration, the Socorro GEODSS site was weathered out 2 days and the Maui GEODSS site was weathered out 1 day. The SOA sensor could have tracked and reported observations on many of their tasked objects and minimized the weather outage impact on the SSN.

B. Summary of Results

1. AFRL Results Summary

Table 2 summarizes the observation throughput and acquisition rate for several nights during the pretest period and over the two-week test period. The columns show:

- the day of year (Julian Date),
- observation time period in hours for statistics (Hrs),
- the number of raw counts, (This is the number of attempts for the night, minus the number of W events, plus the number of additional acquisitions. (# cnt))
- the number of images that had less than 6 stars detected indicating red weather or dome blockage (W),
- the number of images where the catalog star matching failed due to either invalid equatorial coordinates in the header or insufficient number of catalog stars detected (U), (This number indicates red weather or red equipment.)
- the number of image series where the tasked object was not detected (N),
- the number of image series where the tasked object was detected but less the 5 metrics marks (partial acquisition) were generated (P),
- the number of image series where the tasked object was detected and 5 or more metric marks (full acquisition) were generated (Acq), (This number includes the number of additional acquisitions.)
- the number of additional objects detected within an image, excluding the tasked object (AddAcq),

Day	Hrs	#cnt	W	U	N	P	Acq	Add Acq
191	0.81	31	0	2	11	3	15	4
195	4.6	147	1	21	54	21	51	10
196	3.9	156	8	26	70	11	49	8
199	3.3	105	0	12	22	11	60	14
209	3.4	156	4	18	25	31	82	47
210	7.5	277	3	26	82	46	123	28
212	3.7	131	1	17	38	24	52	12
213	7.4	292	2	25	75	53	139	38
216	3.7	128	3	16	33	19	60	17
217	7.3	225	1	31	99	17	78	19
218	7.7	271	4	35	126	31	79	14
219	7.6	158	88	50	84	1	23	1
223	7.8	201	54	33	101	22	45	11
224	7.8	238	38	35	108	18	77	21
225	7.8	269	30	25	128	24	92	14
226	6.1	109	81	25	45	9	30	8
Total	90.41	2894	318	397	1101	341	1055	266

Table 2 Observation Throughput and Acquisition Rate by Day

One of the benefits of this system is its use of astrometry, where the position of the stars determines the position of the satellites, sometimes called in-frame metrics. Not only is the accuracy of the observations better than with a system that uses mount encoders, but if multiple satellites appear in the image, the positions of all of the satellites can be determined simultaneously. The current GEODSS system does not use astrometry and therefore does not get the advantage of these serendipitous collects.

The result of the SOA approach is there were a number of images where multiple satellites appeared in the image. SOA reported all of those satellites. AFRL performed an analysis on the "bonus" satellites, and most of them were on the tasking list. Because of this, and because any satellite observation obtained would be useful to 1 CACS, these bonus satellites were included in the track count.

There are some instances where SOA obtained partial tracks on satellites. This is not the case for satellites tracked in sidereal mode. For satellites tracked in stare mode, however, where three images of the satellite were required, there were occasions when only one or two of these images included the entire satellite track. Although these images did not satisfy the requirement of five satellite observations with ten second intervals between observations, the information provided is still of benefit to 1 CACS, and can be used to update the catalog. Because of this, we counted partial tracks as part of the system performance. These partial tracks are also included in the results.

Based on the discussion later in the report, the throughput of the system, if operated in a mode consistent with what was learned during this test, is between 40 and 45 satellite attempts per hour. The actual throughput during the demonstration was somewhat lower because of an easily solved inefficient coupling between the scheduler and SOA.

Table 3 is a brief chronology of the operational status of the SOA system:

28 Jul 98	Day 209	The system collected metric data only during the second half of the night after the system re-booted.
29 Jul 98	Day 210	The system collected metric data all night.
30 Jul 98	Day 211	The telephone line at Edwards Air Force Base was not plugged into the STU; thus, the system could not communicate with the ODSP.
31 Jul 98	Day 212	The system collected metric data for the first half of the night. After the re-boot in the middle of the night, there was a failure with the following error message: "PC Time-out waiting for FITS files."
1 Aug 98	Day 213	The system collected metric data all night.
2 Aug 98	Day 214	The communication equipment failed because it was not plugged into the UPS. We had to re-initialize the equipment.
3 Aug 98	Day 215	The SOA system at Edwards Air Force Base could not communicate with the ODSP system because the STU key was not plugged in at ETS.
4 Aug 98	Day 216	The system collected metric data for the first half of the night. After the re-boot in the middle of the night, there was a failure with the following error message: "PC Time-out waiting for FITS files."
5 Aug 98	Day 217	The system collected metric data all night however, the sky map that ODSP uses to schedule was not completed before the SOA system connected. Thus, the number objects available for the SOA was limited.
6 Aug 98	Day 218	The system collected metric data all night.
7 Aug 98	Day 219	The system collected metric data all night.
8 Aug 98	Day 220	The SOA system at Edwards Air Force Base could not communicate with the ODSP system because the crew at ETS was not available.
9 Aug 98	Day 221	The SOA system at Edwards Air Force Base could not communicate with the ODSP system because the crew at ETS was not available.
10 Aug 98	Day 222	The SOA system at Edwards Air Force Base could not communicate with the ODSP system because all the allowable sockets were utilized from trying to connect the previous 2 nights.
11 Aug 98	Day 223	The system collected metric data all night. However, there was red weather at the beginning of the night.
12 Aug 98	Day 224	The system collected metric data all night. However, there was red weather at the beginning of the night.
13 Aug 98	Day 225	The system collected metric data all night. However, it was raining until UT 5:32 p.m.
14 Aug 98	Day 226	The system collected metric data all night. However, there was red weather at the beginning of the night

TABLE 3 Nightly Operational Status During Autonomous Test Period

As the chronological data shows, the availability and operational status of the autonomous SOA telescope and data analysis system was high. The failure of metric data collection was due to the "human in the loop" aspects of the SOA demonstration where the ODSP system required a person to bring up the system daily. The chronological data also demonstrates that the communication equipment may not be the best choice due to the reliability and the security aspects of needing a "man in the loop."

2. MIT/LL Results Summary

Table 4 provides a night by night statistical summary of the performance of the SOA system during the 18-day demonstration period. We derived these statistics from the operational ODSP logs using automated report generation software at the ETS. The statistics given in Table 4 differ by those given in Section 1 in three important ways. First, the number of successful acquisitions is limited to only that data which was correctly correlated against either the originally scheduled object or another tasked object (the quality of the correlator used at the ETS was superior to that used by AFRL). Second, a successful acquisition must contain at least as many observations as the original tasking suffix indicated (partial tracks are indicated as Miss X). Third, observations received that are more than tasking, or have no tasking are not counted as a successful acquisitions except in the Total Obs and Extra Obs columns. In addition, we deleted days in which the ETS received no data.

During the 18-day test period, the SOA system produced nearly 6000 metric observations. This represents an average observation rate of a 76.35 obs/hr. The SOA system had a mean acquisition rate of 6.48 tracks/hr when we count only successful acquisitions that are applicable directly against sensor tasking. Approximately 18% sensor attempts resulted in the successful collection of a complete metric track that are applicable against tasking. Acquisition rate peaked as high as 30% on 98:216, during which the sensor collected 44 successful tracks in 3.7 hours of operation (11.9 tracks/hr). A comparison of objects/site of baseline GEODSS, refurbished GEODSS, and SOA is included in Table 11.

Day of Year (1998)	Ops Time (hr)	Attempts	Extra Attempts	Acquire	Acquisition Rate (trk/hr)	Miss	Miss (W)	Miss (N)	Miss (U)	Miss (X)	Total Obs	Extra Obs	Retag Obs
209	3.4	109	60	29	8.5	66	4	23	18	21	458	313	166
210	7.5	265	58	69	9.2	156	3	85	26	42	867	522	64
212	3.7	152	11	37	10.0	86	1	40	17	28	368	183	35
213	7.4	278	90	69	9.3	140	2	80	25	33	987	642	88
216	3.7	147	6	44	11.9	82	3	34	16	29	398	178	28
217	7.3	222	26	46	6.3	159	1	104	31	23	501	271	26
218	7.7	276	29	46	6.0	206	4	132	35	35	525	295	8
219	7.6	256	7	16	2.1	226	88	86	51	1	140	60	0
223	7.8	260	16	24	3.1	219	54	105	33	27	335	215	10
224	7.8	272	32	42	5.4	206	38	112	35	21	525	315	58
225	7.8	309	24	63	8.1	223	30	139	25	29	635	320	33
226	6.1	202	8	19	3.1	166	81	46	27	12	201	106	10
Total	77.8	2748	367	504	83	1935	309	986	339	301	5940	3420	526

1. Ops. Time: Reported operational time from Reference.
2. Attempts: Number of SOA sensor scheduling instances during operational period.
3. Extra Attempts: Number of unsolicited or serendipitous responses from the sensor (miss or data).
4. Acquire: Number of successful acquisitions that were consistent with the original tasking suffix and properly correlated against the scheduled object or another tasked satellite.
5. Acquisition Rate: Number of successful acquisitions divided by operational time in hours.
6. Miss: Total number of reported unsuccessful acquisitions or partial acquisitions.
7. Miss (W): Total number of unsuccessful acquisitions attributed to weather by the SOA sensor.
8. Miss (N): Total number of unsuccessful acquisitions attributed to non-weather causes by the sensor.
9. Miss (U): Total number of unsuccessful acquisitions due to image header coordinate error in the SOA sensor.
10. Miss (X): Total number of incomplete tracks reported by the SOA sensor.
11. Total Obs: Total number of metric observations received from the SOA sensor.
12. Extra Obs: Total number of metric observations received for which there was not applicable tasking.
13. Retag Obs: Total number of metric observations retagged to a different satellite number or UCT by the ODSP correlator.

Table 4. SOA Sensor Performance Summary

C. Detailed Results

The Appendix contains a night-by-night evaluation of the system performance. The following sections discuss results and recommendations on various aspects of the demonstration.

1. Synchronous Scheduling and Data Processing/Delivery

One of the fundamental assumptions of the ODSP design is that participating sensors are providing verification of successful acquisition and metric data in near real-time. From the perspective of the centralized scheduler, this is critical as it dynamically modifies future scheduling decisions based on the success or failure of previous attempts. From the sensor perspective, if the sensor is unable to process acquired frame sets into metric observations at least as fast as it observes new objects, a backlog of unprocessed data accumulates at the site. Worse, the centralized scheduler is forced to either "commit" an increasing number of objects to the site with no assurance the objects have been tracked or to redundantly schedule these objects to another site.

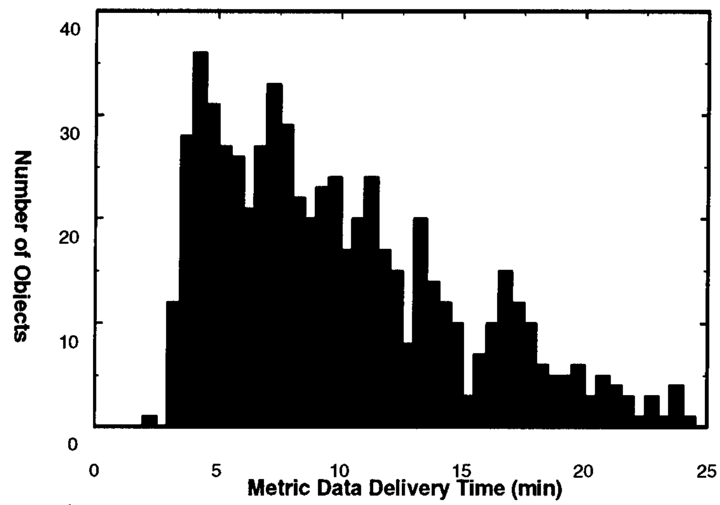


Figure 17 Histogram of Metric Data Delivery

Figure 17 shows the metric data delivery time for the SOA sensor during the 18-day test period. Data delivery time is the elapsed time from the initial scheduling instance until the PC delivers data to the ODSP. A detailed review of the logs shows that under optimal conditions, SOA typically delivered data in 4-5 minutes.

Figure 18 shows the start-up sequence and communication between the telescope control PC, data processing workstation, and ODSP scheduler. The SOA telescope and CCD has the ability to download the image of the current object, while slewing to the next object. The scripts executed by the telescope control PC illustrate this need for multiple tasked objects. To maximize the throughput of the SOA sensor, Odin requests three tasked objects (A-C) before transmitting the metrics of object A. However, this delay between object tasking and reporting had important ramifications on the throughput of the SOA system during testing as it interacted with the ODSP scheduler.

When a satellite is scheduled by ODSP, the object (or more specifically, the tasking associated with the object) is "committed" to the sensor for a specific period. During this interval, ODSP will not schedule the object to another sensor in the network. Once the sensor responds to the scheduling with either a miss code or data, the object is no longer committed and ODSP may again schedule it to any sensor should any tasking remain on the object. ODSP developers imposed the time limit to ensure that it eventually reschedules an object to other sensors should the original sensor fail to respond within a reasonable time. For the SOA demonstration, we set this time limit to 5.0 minutes. However, a review of the ODSP operational logs shows that a time of approximately 20 minutes would have been more appropriate.

Telescope Control PC	Data Process Workstation (Odin)	ODSP
	Check weather & sunset	
	Send start script to PC	
Start telescope & open dome	Connect to ODSP	
(10-12 minute startup time)	Wait for Connection Status	Send Connection Status
	Ask ODSP for Schedule	
	Wait for Tasked Object List	Send 10 Tasked Objects (A)
	Ask ODSP for Schedule	
	Wait for Tasked Object List	Send 10 Tasked Objects (B)
	Create Obs A script & send to PC	
Execute Script	Ask ODSP for Schedule	
Slew to A	Wait for Tasked Object List	Send 10 Tasked Objects (C)
Image A Slew to B		
	Create Obs B script & send to PC	
Send Image A to Odin	Wait for Image A from PC	
(Total time: 1-1.5 minutes)		
Execute Script		
Slew to B	Process A & send obs to ODSP	Receive obs for A
Image B Slew to C	Ask ODSP for Schedule	
	Wait for Tasked Object List	Send 10 Tasked Objects (D)
Send Image B to Odin		
(Total time: 1-1.5 minutes)	Create obs C script & send to PC	
	Wait for Image B from PC	
Execute Script		
Slew to C	Process B & send obs to ODSP	Receive obs for B
Image C Slew to D	Ask ODSP for Schedule	
	Wait for Tasked Object List	Send 10 Tasked Objects (E)
Send Image C to Odin		
(Total time: 1-1.5 minutes)	Create obs D script & send to PC	
	Wait for image C from PC	
	Process C & send obs to ODSP	Receive obs for C

Figure 18 SOA Start-up and Operations Sequence

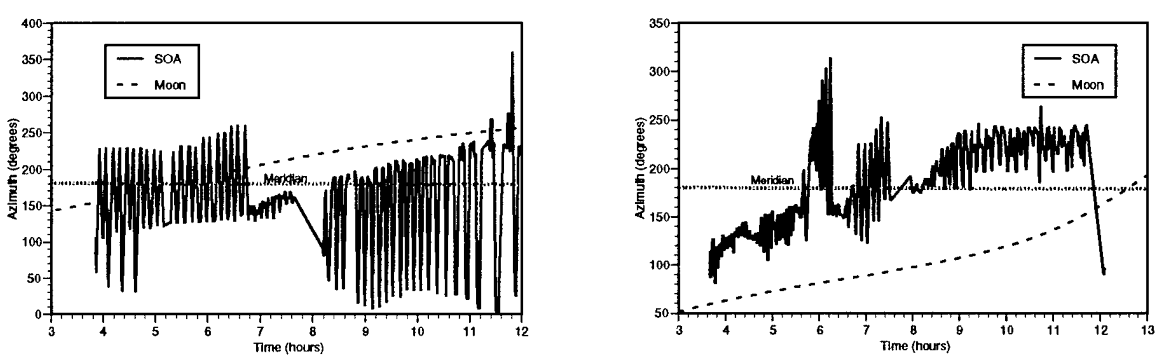
Despite mitigation strategies, the late delivery of data to the ODSP had some unanticipated side effects when ODSP scheduled the SOA sensor to track a satellite in a cluster of other tasked satellites. Normally, the ODSP schedules a single object. If the sensor is capable of acquiring data on multiple objects in the field of view, ODSP receives this data as "serendipitous" data and applies it appropriately against tasking. However, due to delayed data delivery, the ODSP did not know that SOA had tracked nearby objects until several minutes after the next scheduling instance. Consequently, SOA would multiply track cluster members, artificially increasing the throughput of the sensor and providing redundant data to the SCC.

In order for ODSP to integrate successfully sensors with slower metric delivery times, it could take one of three actions. First, an appropriate "commit time" must be determined for the capabilities of each sensor. For the SOA demonstration, we used 5 minutes. However, as the above analysis shows, 20 minutes would have been better. This will ensure other sensors are not scheduled to track objects which the augmenting sensors are still "working on." Second, all objects within the field of view and tracking capabilities of the sensor should be committed to the sensor by the scheduler. Although this would add computational complexity to the OC^3F dynamic scheduling algorithms, it would prevent the redundant cluster tracking discussed above. Third, and potentially a simpler solution is to alter slightly the SOA software to compensate for this delay.

2. Throughput

The throughput of the system, if operated in a mode consistent with what was learned during this test, is between 40 and 45 satellite attempts per hour. The numbers were somewhat lower during the demonstration due in large part to the unoptimized interaction of the telescope and the scheduling software.

Looking at two days, day 217 and day 225, one can see the effect of optimization. Figure 19 shows the azimuth position as a function of time for those days. Notice that what is shown in most of these plots, regardless of day, is that the telescope is being sent back and forth, often from low on the horizon in one direction to low on the horizon in the opposite direction. This is due to the lag time associated with the scheduling process and the telescope motion. The result is that the telescope is spending an inordinate amount of time moving back and forth. It becomes much worse when the telescope moves back and forth across the meridian (the line dividing East from West). Because of the design of the mount, the telescope must move to the South, cross the meridian, and then move back North.



Day 217 **Day 225**

FIGURE 19 Throughput Comparison between Day 217 and Day 225

Day 217 is an example of a bad case. Not only is the range of telescope motion quite large, but it continually crosses back and forth across the meridian. Indeed, if one looks at the throughput for day 217, it is only 28 satellite attempts per hour. The only time during this day where the mount operates in the desired mode is from about 0645 hrs to 0730 hours. During this period, the throughput is 44 satellite attempts per hour.

Day 225 is a good case, when the throughput is 40 satellites per hour. Although there is some "ringing" in the motion of the telescope in azimuth, it is not very large, and seldom crosses the meridian. The throughput for the last half of the night is 45 satellites per hour. The throughput is at its worst (29 satellite attempts per hour) during the third hour (0600-0700), when the telescope is moving back and forth across the meridian.

It is important to note that this is a very easy problem to solve. We can solve the problem either at the scheduler, or at the SOA controller. The problem arises from time lag between satellite tasking and reporting. One solution is for the SOA to request a satellite, not based on the current position of the telescope, but either at the desired position of the telescope (good phase angle), or the position where the telescope will be when it's ready for the next satellite. Either case would better optimize the telescope motion thus increasing throughput.

If the system were in operation today, with this excessive mount motion reduced, its throughput should be in the range of 40 to 45 satellite attempts per hour, as demonstrated on both of the days analyzed.

3. Satellite Tracking Mode

For the SOA demonstration, MIT/LL added an additional descriptive field to the satellite database in ODSP to indicate the proper tracking mode for the satellite. The two-valued field indicated that the object was best observed in rate track (stare tracking) mode (satellite stationary), or streak detect (sidereal tracking) mode (background stars stationary). In stare tracking, the telescope position is fixed, causing the stars to appear as streaks moving at sidereal rate and along the equatorial axis, while geostationary satellites appear as point sources and other deep space objects appear as streaks at arbitrary angles and rates. In sidereal tracking mode, the telescope moves to compensate for the rotation of the Earth, so stars appear as point sources whereas satellites generally appear as streaks.

Both tracking modes have their advantages and disadvantages. For dim or flashing near-geostationary objects, stare tracking mode allows the satellite irradiance to dwell and accumulate on just a few pixels, providing a higher signal to noise ratio and improving the probability for detection. The disadvantage of stare tracking is that the streaking stars tend to clutter the image background, increasing the opportunity for bright stars streaks to overlap onto dim objects, and may often require multiple images to achieve the requirement of 5 metric marks. Sidereal tracking assures that satellites will appear as distinct streaks against a background of point-like stellar objects. By opening the shutter for 20 seconds, closing it for 10 seconds, and opening it for 10 seconds before downloading the images from the CCD, the velocity vector for the satellite is uniquely determined and the endpoints of each streak along with the center of the 20 second streak provides 5 metric marks separated by 10 seconds each. The sidereal tracking disadvantage is the corollary to stare mode's advantage; the satellite irradiance is smeared along a range of pixels at sidereal rates or higher.

Figure 20 shows the display output of processing a satellite in sidereal mode. The stars highlighted with circles indicate stars matched with catalog star positions. The square marks indicate computed satellite metric positions, which the PC transmits to the ODSP system. Figure 21 shows the detection of two satellites during ballistic tracking. Although one satellite point image is in a star streak, the image processing software is still able to detect the satellite object.

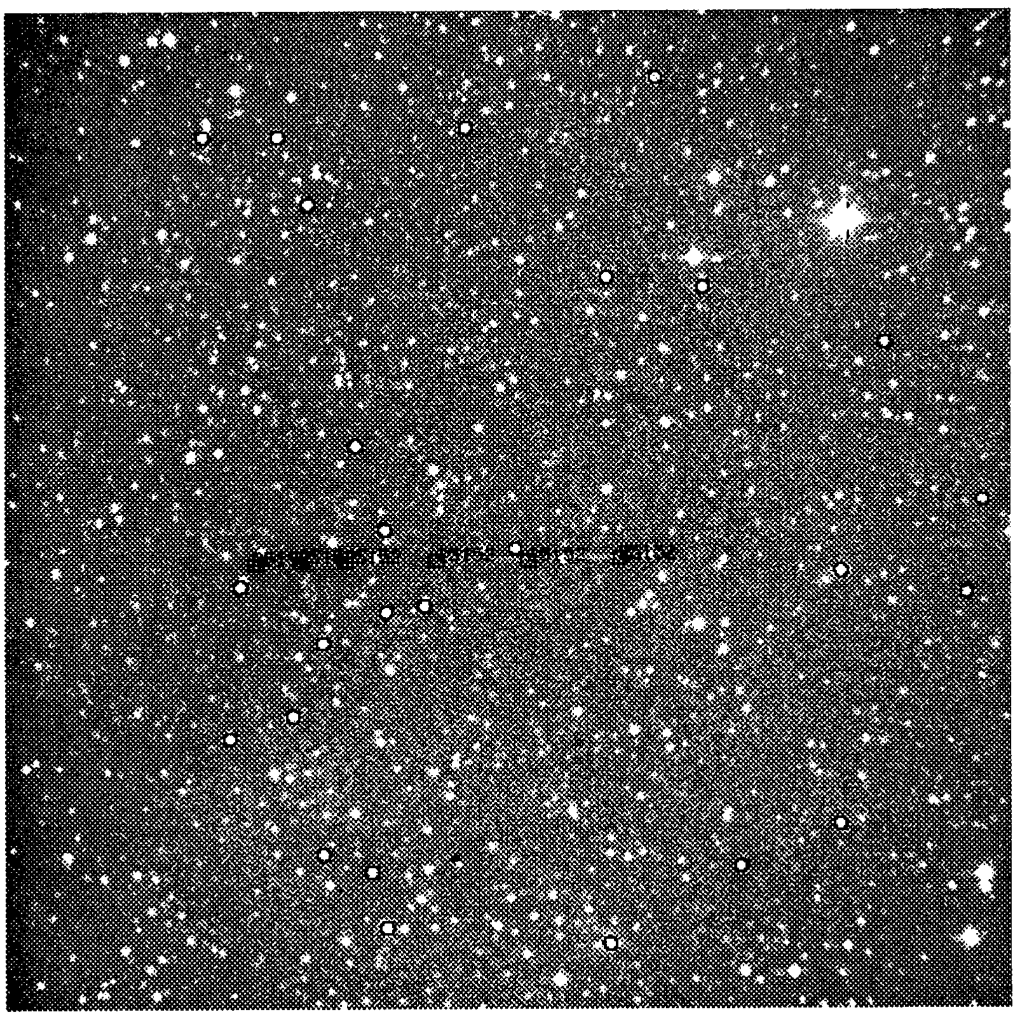


FIGURE 20 Satellite image processing on Odin from sidereal tracking

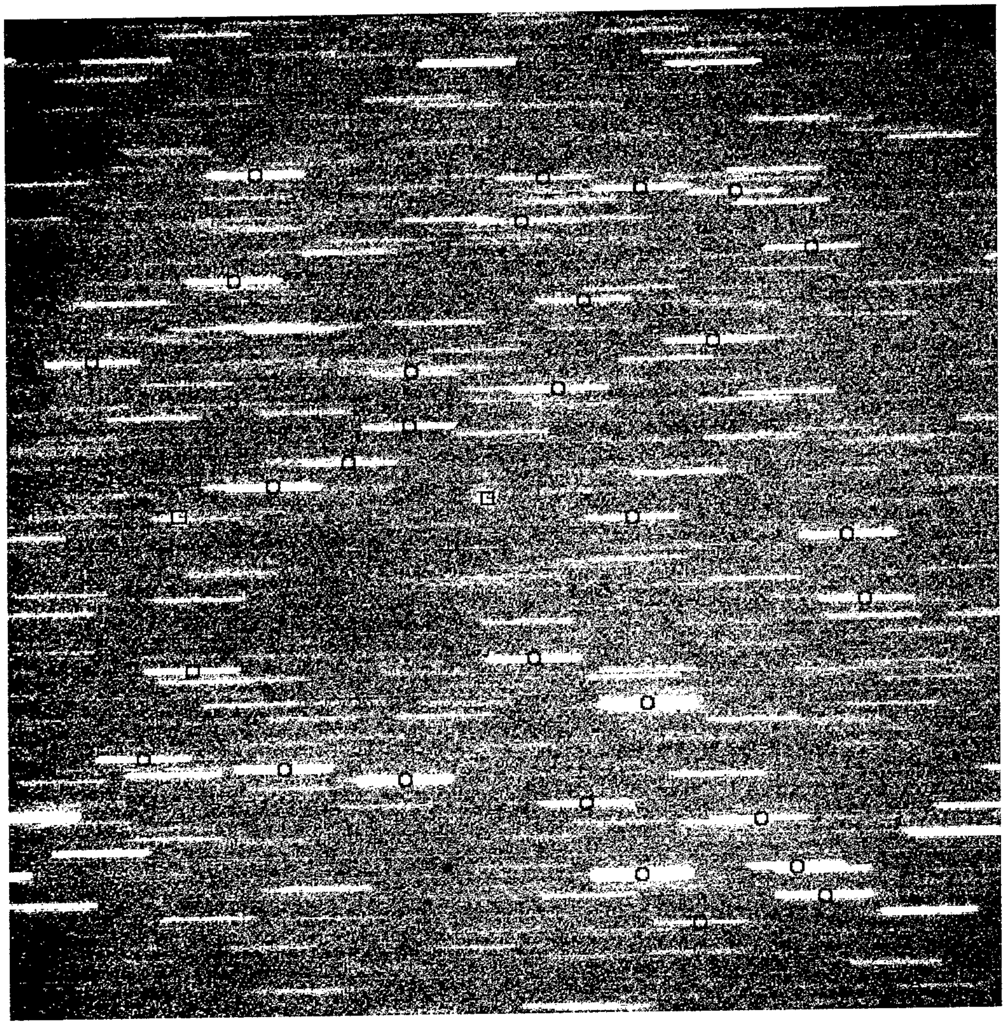


FIGURE 21 Satellite image processing on Odin from stare tracking

In pre-deployment and site integration tests, Maui, HI and Edwards AFB, CA observed a large portion of unclassified satellites. A visual observer selected the tracking mode for each satellite based on the brightness and temporal characteristics of the satellite and stored in a satellite information database. Although a significant number of satellites were observed, the list of satellites with optimized tracking strategies was not complete, in particular, excluding a large fraction of classified satellites. Continued supervised testing can extend this list and improve acquisition rates.

4. Minimum and Maximum Tracking Rate

Because of the narrow field–of-view (FOV) of the telescope, one-half degree, MIT/LL added a minimum and maximum tracking rate screen to ODSP. For the demonstration, this prevented scheduling of any objects with an angular rate less than 4 arcsec/sec or greater than 24 arcsec/sec. Figure 22 shows the angular velocity distribution of the visible deep space population[6] at a particular instant. The vertical reference lines indicated the 4 arcsec/sec and 24 arcsec/sec scheduling screens. Only six of the visible objects had angular rates below the 4 arcsec/sec minimum screen. Of these, three were highly eccentric super-synchronous objects. However, 109 objects (21% of deep space objects) had angular velocities greater than the 24 arcsec/sec maximum screen. This is a significant fraction of deep space objects that were unavailable to the sensor. A telescope with a 1-degree FOV would double the tracking rate from that used in the demonstration (1/2-degree FOV) and increase to 48 arcsec/sec the tracking rate limit of the system. This increase in FOV would add approximately 85 more objects and decrease the percentage of objects that had angular velocities greater than the new 48 arcsec/sec maximum screen to 5% of deep space objects. We recommend that the FOV of the telescope be one of the design considerations in acquiring a SOA-like system. An alternative to a wider FOV is to observe these objects at other times, when the angular velocity are within the capabilities of the sensor, or schedule the objects to other sensors.

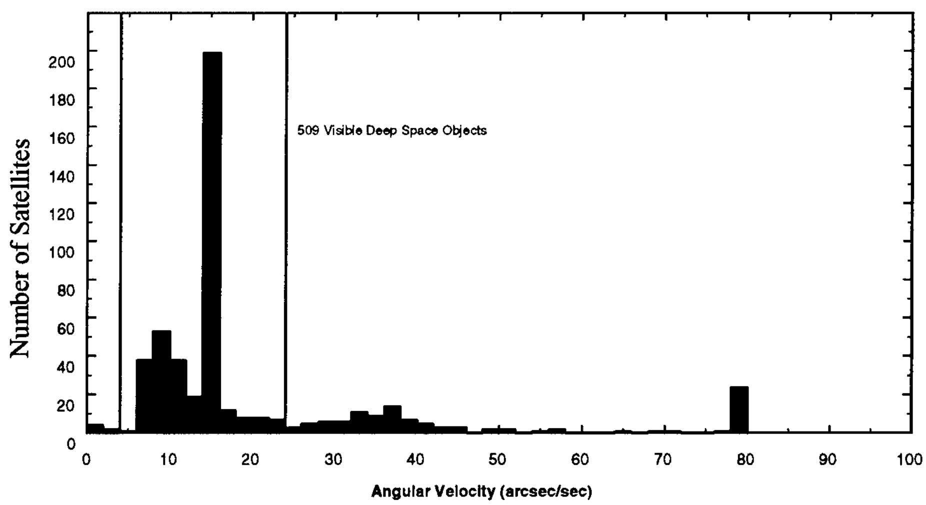


Figure 22 Angular Velocity Distribution of Deep Space Satellites

5. Adjustment of Existing Scheduling Weights and Screens

One of the essential features of the centralized scheduler is the ability to set sensor specific values of the various weights and screens for different sensors. This feature can both implement different scheduling philosophies for different sites and adjust sensor scheduling for special capabilities or limitations of particular sensors. For example, by adjusting the tasking priority weights, it can dedicate certain sensors to high priority objects.

[6] Here, deep space is defined as any object having a period longer than 225 minutes.

For the SOA demonstration, MIT/LL adjusted several of the previously existing (TOS) ODSP scheduling weights and screen values to the telescope performance characteristics.

Table 5 shows some of the key scheduling parameters used for the SOA demonstration period taken from the ODSP operational logs on 98:223. For comparison, we also show the currently used TOS scheduling.

Scheduling Criterion	SOA Sensor	TOS	Comment
Element Set Age	-2	1	This unusual setting caused satellites with younger element sets to be scheduled first.
Telescope Slew Angle	6	1	This strongly weighted slew distance, which minimized slew distance between successive tracks.
Dome Slew Angle	2	1	
Elevation Rate	2	1	
Elevation	2	1	
Solar Phase Angle	4	1	Phase angle strongly effects satellite brightness. This weight improved the likelihood that satellites were only scheduled at favorable phase angles.
Galactic Latitude	>7.5°	No screen	The SOA star field recognition algorithms would run more slowly with high background star density. This preventing scheduling of objects against the Milky Way where star density was high.
Tasking Category 1	0	36	For SOA, all higher weighting of higher tasking categories was disabled.
Tasking Category 2	0	24	
Tasking Category 3	0	14	
Tasking Category 4	0	8	
Tasking Category 5	0	0	

Table 5 SOA Demonstration Scheduling Criteria

Note that there was confusion between MIT/LL, the Space Battlelab, and AFRL on the exact operation of the scheduler. The Space Battlelab requested MIT/LL apply filters based on the following criteria:

Element set age: <14 days
Phase Angle: <60 degrees
No changes to Tasking Priority

However, the scheduler could not put in upper limits, instead it could only optimize for minimum phase angle and element set age. In addition, ODSP's Tasking Priority weights were off. We will discuss the unfortunate effect on the demonstration of this misunderstanding in further detail in the subsequent sections.

a. Element Set Age

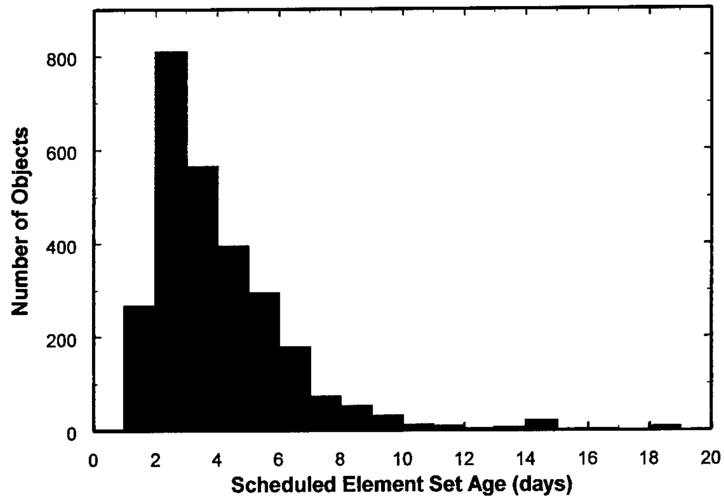


Figure 23 Histogram of Field Element Set Age at Scheduling

Element set age is a controversial scheduling criteria. Although the GEODSS A-Specification requires its use as a scheduling criterion, it does not specify exactly how to use the criterion. From the sensors point of view, element set age is often used as an indicator of element set quality (older element sets have greater error).[7] In theory, a sensor site should not have weight by element set age at all and rely completely on the tasking category assigned to the object by the 1 CACS. Thus, when a sensor uses element set age as a scheduling or mission planning criterion, it is used only to "break ties" between tasking at the same category. Generally, ODSP gives the older element sets greater priority, using the logic that 1 CACS needs data more desperately on these objects. The current implementation of the ODSP uses a simple linear weighting function for element set age.

However, during the SOA demonstration we anticipated that the narrow field of view of the SOA sensor would require younger element sets to increase the probability of successful acquisition. The desire was to have element sets age less than 14 days old (a filter). Unfortunately, the ODSP could only minimize the age of the element sets. Figure 23 shows the dramatic effect of this criterion to the overall scheduling of the system. This created the strong tendency for the ODSP to schedule young element sets to the SOA sensor.

Fortunately, there were a large number of satellites tracked with element set ages greater than 4 days, Figure 24 shows consistent acquisition rates for element set ages out to 12 days old. Considering the SOA acquisition did not show dramatic dependence on element set age, it should not be a major consideration in scheduling objects to SOA.

[7] Since 1 CACS issues new field element sets only when they degrade beyond a particular value from the element set maintained internally at SCC, this indicator is not necessarily correct. Nonetheless, as a general rule, the older field element sets will indeed have higher error at the current epoch.

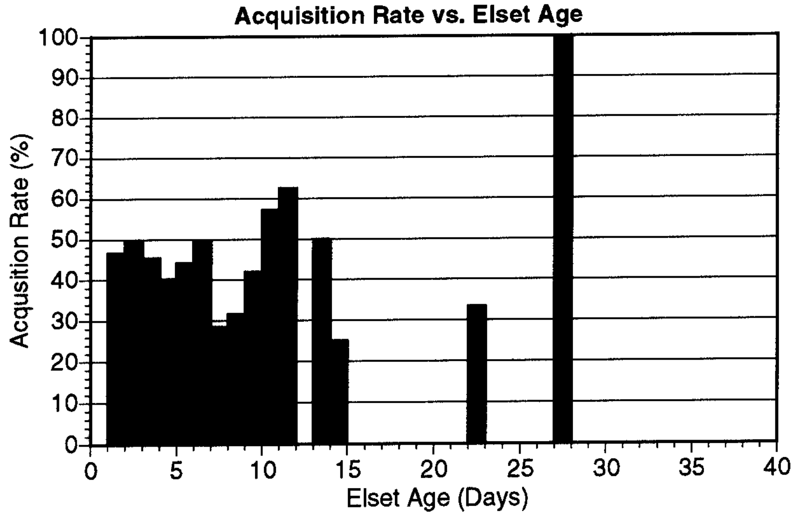


Figure 24 Acquisition rate as a function of element set age

b. Phase Angle

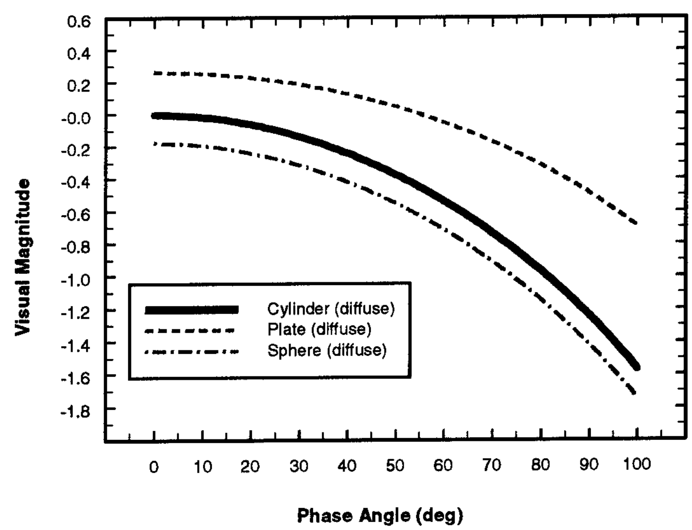


Figure 26 Phase Functions of Generic Objects

Solar phase angle[8] strongly effects the observed brightness of satellites when viewed from the Earth. Typically, GEODSS and other optical sensors attempt to observe fainter satellites at favorable phase angles when they are easier to detect. For geosynchronous satellites, the most favorable phase angles typically occur shortly before the satellite enters Earth shadow. Figure 26 shows the effect of phase angle on generic shaped objects. Here, it represents the phase in terms of the satellite brightness in visual magnitudes relative to the diffusely reflecting cylinder. As can be seen from the graph, typical diffusely reflecting objects show little decrease in brightness for phase angles less than 20-30°. However, for phase angles approaching 90°, satellite brightness decreases by 1.2 to 1.4 visual magnitudes. For typical geosynchronous satellites, this can easily be the difference in a successful detection or missing the object, even for a 1-meter class GEODSS telescope. Chronically tracking a particular satellite at a near-optimal phase angle has a subtle and detrimental effect on element set quality, particularly when the same site usually tracks the satellite. Historically, this has been a problem with sensor data collected by the GEODSS network. For this reason, Unified Instruction UI10-40 specifically encourages sites to "strive to sample different parts of the orbit on different

[8] In this report, phase angle refers to the Earth/Sun angle as observed from the satellite.

attempts." Additionally, 1 CACS tasks objects to multiple sites in an attempt to gain sampling along different parts of the orbit. In the future, the OC^3F will specifically schedule objects to obtain this sampling without having to schedule multiple sites.

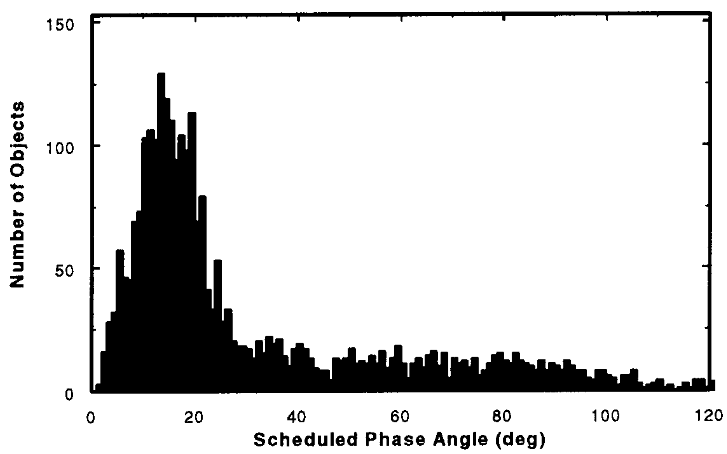


Figure 27 Phase Angle Distribution of Scheduled Satellites

The desire was to have phase angles less than 60 degrees (a filter). Unfortunately, the ODSP could only minimize the phase angle. Figure 27 shows the distribution by phase angle of all scheduling instances during the 18-day demonstration. As can be seen, ODSP scheduled nearly all of the satellites when the phase angle was less than approximately 22º. Under these conditions, the diffuse magnitude of the satellite very minimally degrades.

SOA's acquisition rate remained high between solar phase angles of 10 and 60 degrees. Moreover, intelligent scheduling can task these ranges of solar phase for both sides of the Earth's shadow for high elevation deep space objects. Therefore, one can measure some 50 to 100 degrees of the orbit of the satellite.

Phase angle should still be a consideration in tasking a SOA sensor. However, a maximum angle, approximately 60 degrees, should be set. There is no need to optimize for minimum phase angle.

c. Telescope and Dome Slew Distance

Telescope and dome slew times are primary factors increasing the time for a sensor to track a particular satellite. For the purposes of efficiency, GEODSS, TOS, and other optical space surveillance systems generally minimize the slew distance between subsequent satellites. This increases system throughput by decreasing the amount of time the system spends waiting for the dome and telescope to slew to the correct position. Unfortunately, operational requirements may require long slew distances, particularly to satisfy tasking of category 1 and 2 objects early in the evening. Consequently, most telescopes used for space surveillance application have high speed mount and dome systems. For example, the GEODSS telescope is able to track at rates up to 2 degrees/sec and slew at rates up to 10 degrees/sec.

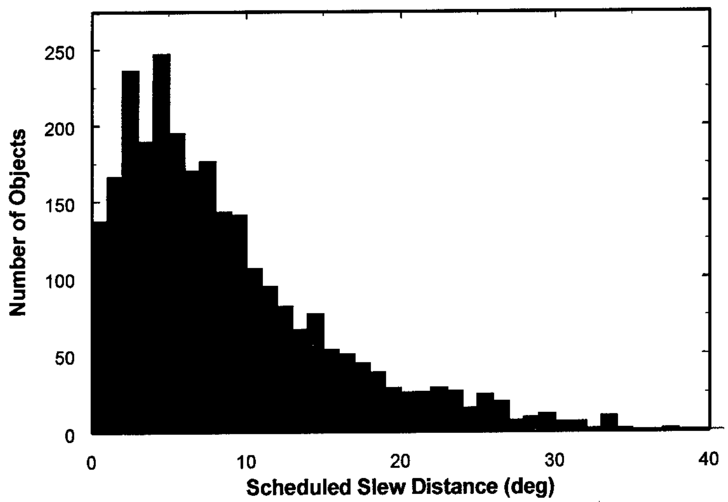


Figure 29 Distribution of Slew Distance

The telescope mount used for the demonstration was a "German Equatorial" type. One limiting physical characteristic of this mount is that motion from one side of the meridian to the other requires a 180° rotation in the equatorial axis, as well as some motion in declination. Most low cost, commercial, astronomical telescopes, including the Paramount used in SOA, have limited maximum slew rate, generally around 4-5 °/second, requiring 30 seconds to 2 minutes to move between the hemispheres about the meridian. MIT/LL designed the ODSP scheduler to work with the fast-slewing GEODSS telescope on a forked equatorial mount, which do not experience this meridian-crossing constraint. Consequently, when ODSP uses the weighted selection criteria such as minimal mount motion for SOA, the angle computed for a meridian crossing does not represent the true angle the SOA telescope must slew. As can be seen from Figure 29, the scheduler was effective in minimizing the slew distance for the sensor. Of the 2743 scheduling instances during the 18-day demonstration, 48% required a slew distance of less than 6°, 70% less than 10°, and 82% less than 15°. However, this did not necessarily minimize the time required to slew the telescope.

Currently, the ODSP schedules uses a very simple linear cost function for both telescope and dome slew distance. In future demonstrations, one could easily develop a more complex cost function to represent the unusually long slew times when the telescope must cross the local meridian. An alternative approach, without modification to ODSP, is to modify the Odin executive process to select only tasking in the east (azimuth < 180°) until local midnight (0800 UT) and then select only tasking in the west (azimuth > 180°) after midnight. Odin would reject all other tasking with a miscode 'X'. We tested neither of these options during the demonstration.

d. Satellite Category

1 CACS assigns every satellite tasked by the SCC for metric observation a category and suffix to define the priority and data requirement for the satellite. The tasking category (specified by an integer between 1 and 5) defines the priority for taking observations and resolves tracking conflicts when two or more satellites are in the coverage of the sensor at the same time. The SPADOC tasker uses the element set quality and age to determine the tasking category. In general, as element set age increases or element set quality deteriorates the tasking category will increase. By definition, Category 1 is special events of the highest priority. The optical sensors use Category 2 for both special events and high priority routine tasking. All remaining lower priority tasking use Categories 3-5. Figure 30 shows a profile of typical GEODSS tasking (actually, this is tasking for the Socorro GEODSS Site for Day 211, during the SOA demonstration). Approximately 18% of the tasking is category 2, 32% category 3, and 50% category 4.

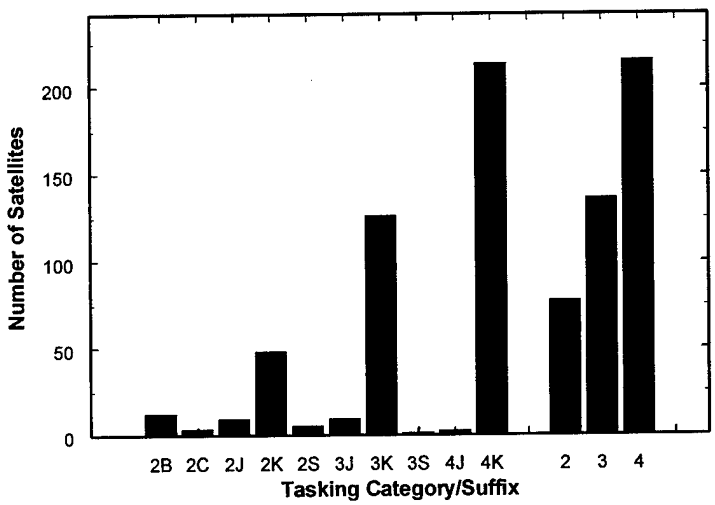


Figure 30 Typical GEODSS Tasking Profile

For typical operations, tasking category is the strongest weighting function. The category weight is strongly weighted towards the higher categories. Because of the category weight differential's design, nearly all satellites tasked at a higher category will generate a scheduler figure of merit greater than all other satellites of lower category. Unfortunately, for the demonstration, the category weighting was disabled. Thus, ODSP scheduled all tasked satellites equally, regardless of category.

With the majority of the AFSPC tasking for routinely observed satellites at category 4, the presumption was SOA would not perform as well for satellites tasked at category 2 or category 3. Figure 30 shows that although almost half of the objects observed were category 4, satellites with a higher priority tasking of category 2 actually had a higher acquisition rate. Category 5 objects generally have well known orbits, resulting in the high 80% acquisition rate recorded. Consequently, SOA shows good acquisition capability independent of satellite tasking category. Moreover, during this observation period the Maui GEODSS spent 70% of the time going after category 3 and 4 objects.

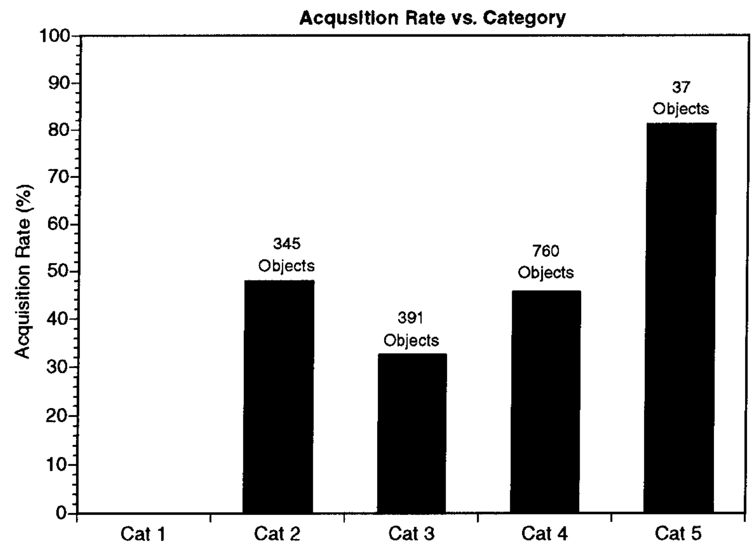


Figure 31 Acquisition Rate vs. Tasking Category

The interesting result in Figure 31 is the lower acquisition rate seen for category 3 satellites. The average optical brightness measured for category 3 and category 4 satellites acquired were both about 13.1 magnitudes. Therefore, SOA's category 3 failed acquisitions are probably not due to SOA's detection sensitivity. In examining a variety of measured parameters, the major difference between category 3 objects from category 2 and 4 objects is the tracking mode selected. Table 6 shows the observation count for each category for both the sidereal and stare tracking modes.

	Category 2	Category 3	Category 4	Category 5
Sidereal	527	918	1778	103
Stare	1039	452	1611	10

Table 6 Observation Count per Category

As evident from the table, category 3 objects were observed twice as often in sidereal mode, while conversely, category 2 objects where observed twice as often in stare mode. Stare mode acquires 3 images each with 10-second exposures, while sidereal model acquires a single image with an exposure time of 40 seconds. Stare mode tracks closely with deep space objects, while sidereal mode causes the satellite image to streak as the telescope tracks the stars. Consequently, stare mode has a higher probability of acquisition for objects offset from its predicted position. By increasing the selection of stare mode tracking for category 3 objects, a higher acquisition rate should be possible.

6. Centralized Correlation

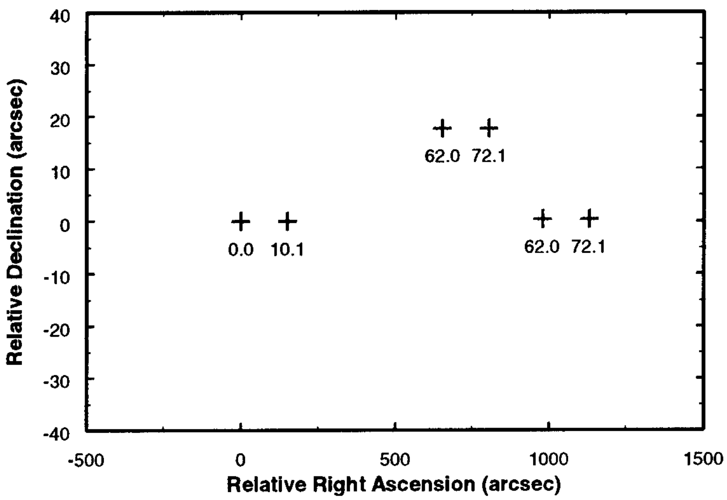


Figure 32 Schematic of Sensor Misstag

We demonstrated the utility of centralized correlation throughout the 18-day demonstration. Of the 5940 metric observations received by ODSP, 526 (8.9%) were retagged by the correlator. Figure 32 schematically shows one particular example, taken from 98:209. Here, ODSP scheduled the SOA sensor to track a geosynchronous object. In response to the scheduling, the SOA sensor replied with 6 observations, all labeled with the same SCC number. Figure 32 shows the observations with the relative right ascension and declination in arc seconds. It annotates the relative time next to each observation. However, the correlator associated the lower four observations with a deep space UCT and only the upper two observations with the originally scheduled object. Only the two appropriately associated observations were applied against tasking, resulting in a missed attempt. In a full network demonstration, ODSP would have rescheduled this object, perhaps to a different sensor, to satisfy the tasking.

This is an example where AFRL data would indicate an "acquired" object, but MIT/LL would not. This is a limitation on the correlator used during the SOA demonstration, not on the augmentation concept.

7. Dome Blocking at the Meridian

An infrequent effect of the SOA German Equatorial mount and dome occurs during small angular motions across the meridian. During this period, TheSky software commanding the telescope will try to "cheat" and not rotate the equatorial axis by 180°, but slew the declination axis to look over the mount. The problem arises in that the dome, following the telescope motion, assumes that the telescope has done the 180° equatorial rotation and positions the shutter opening accordingly. Unfortunately, for some motions within 3° of the meridian, the dome will block the field of view of the telescope. This occurrence is infrequent and will occur 1-2 times during nightly operations. The data processing workstation interprets this dome blockage as weather and transmits a 'W' miscode to ODSP. The software vendor for TheSky, Software Bisque is aware of the problem and will fix it in a future version of the software.

8. Telescope Control Computer Restart

During site integration, AFRL discovered a memory leak in the dome control process, AutoDome, running in the telescope control computer. This periodic memory leak eventually consumed all the system memory after five hours of operation. The vendor, Software Bisque, plans to correct this error in a future version of TheSky software package. To work around this problem, the data processing workstation, Odin, shuts down the telescope and dome and reboots the telescope control computer after four hours of operation, resetting memory allocation.

There are two disadvantages to this solution. First, the restart sequence consumed 30 minutes of observing time. The second disadvantage had, in some cases, a more prolonged influence on performance. The SOA system originally operated from sunset to sunrise with the starting position of the telescope always fixed at an azimuth of 90° and an elevation of 30°. When AFRL incorporated this restart sequence into the Odin software, the changes necessary to eliminate this "hard-coded" starting angle were too extensive to accomplish prior testing. Consequently, after the telescope control computer restarted near local midnight, it requested tasking from the ODSP scheduler with the telescope reported at a corresponding azimuth of 90° and elevation of 30°. At 0800 UT, satellites in this reported position in the sky had poor phase angle and therefore, reduced probability of acquisition. We assumed ODSP would select a more optimal set of objects, largely ignoring the reported telescope pointing. In many cases, this was true, but in some cases such as Day 209 (28 Jul 98 UT), this effect, coupled with ODSP tasking and reporting delay, lasted for several hours. A better solution would have been to ignore the current telescope position and request tasking from ODSP using coordinates corresponding to brightest satellite illumination and minimum phase angle.

9. Prior Observation Reporting

At nautical twilight before sunrise, the SOA system performs an orderly sequence of shutdown events. Odin sends a script to the telescope control computer to park the telescope, close the dome, and shutdown the PC control software, such as TheSky. However, due to the stacking of tasking to the telescope control computer the telescope control computer may still image and transmit a few remaining observations before shutdown. Depending on the sequence of events, Odin may not process these remaining image files until the start of the next night's operation. The issues arises is similar to the problem described in Section 3C8, the reported telescope azimuth and elevation position for the tasking the fourth object may be in the west, where the phase angle for satellite illumination is large and the tasked object is dim. As in Section 3C8, the assumptions, consequences, and solutions are the same. The ODSP scheduler was expected to largely ignore the reported telescope angle, but in some cases, such as Day 217 (5 Aug 98 UT), the tasking resulted in numerous meridian crossings reducing throughput, and poor phase angle reducing successful satellite acquisitions. The trivial solution to this is reporting a "nominal" telescope-pointing angle, while ignoring reported metric angles, which would have eliminated this performance degradation.

10. Element Set Age and Elevation Tasking Errors

In developing satellite tracking capability in their software, Software Bisque noted that tracking satellites with very old element set ages had a very low probability of acquisition. Therefore, tasking a satellite with an element set age greater than 45 days, results in a scripting error on the telescope control computer and termination of the selected tasked object without the generation of any image files. Due to balance considerations and physical limits of the mount, the SOA telescope also had a hard restriction to remain above 20° elevation. Tasking below 20° also results in a scripting error and no image file generation. We synchronized the telescope control computer and Odin with script and image file transmission. For each script file created and transmitted, Odin waits to receive an appropriate image file from the CCD camera. With scripting errors, this synchronization is broken.

In interfacing with the ODSP scheduler, Odin assumed that tasking a satellite with element set age greater than 45 days would never happen. However, in actuality, the range specification for element set age is not bounded, but serves only to adjust weighting factors. In the case of tasking elevation, although ODSP does eliminate tasking below this elevation limit, since there is a delay between ODSP tasking and actual observation, SOA may exceed this lower elevation limit for non-geostationary satellites.

To alleviate this hurdle to continuous, autonomous operation, AFRL added a watchdog timer to the Odin process waiting for image file transfer. If more than 10 minutes elapsed since last image file transfer, SOA requested new tasking from ODSP, generated a new script file, and the process reset to wait for the next image. With 50 to 55 seconds to reconnect the STU III encrypting modem and router, a total time of 00:10:50 to 00:10:55 was lost between observations. This errant tasking will appear in two successive tasking scripts and result in two successive watchdog time-outs, generating a total reduction of operation time of 00:21:40 to 00:21:50. This watchdog process added to Odin not only recovered from these tasking errors, but also eliminated any unforeseen obstacles to autonomous operation. Watchdog time-outs were noted on Day 210 (29 Jul 98 UT), Day 213 (1 Aug 98 UT), and Day 216 (4 Aug 98 UT).

11. System Accuracy

The accuracy of the observations provided by the SOA system are adequate to support the SSN.

HQ SWC/AE analyzed observations made with the telescope in Maui. In February 1997 they reported the observations ". . . are certainly "as good or better" than GEODSS . . . Your use of inframe metrics has the potential to provide data up to 5 times more accurate than GEODSS." SWC/AE did not have the truth data available to judge absolute accuracy[9].

AFRL/VS analyzed similar telescope observations and concluded the system has ". . . demonstrated the ability to produce topocentric right ascension and declination observations of geosynchronous satellites with noise levels under two arcseconds[10] (one standard deviations)."

12. Advanced Weather Protection System

The SOA version of AWPS went through developmental test and evaluation (DT&E) at ETS for 150 hours before delivery to Edwards AFB. The meteorological conditions during ETS DT&E had no hazardous conditions for testing; so, MIT/LL simulated hazardous conditions. The functions not tested were frozen precipitation and blowing snow or dust. All tested functions of AWPS performed as expected.

MIT/LL integrated AWPS into the SOA Sensor System at Edwards AFB on June 23, 1998. All functions of AWPS performed nominally when interfaced into the data processing computer. The wind speed hazard threshold parameter was modified for Edwards AFB environment. Maximum wind speed was set at 35 mph with an averaging time constant of 10 seconds for gusting winds. The data processing computer watchdog timer constant was set at 15 seconds. The second, dome alarm time constant was set to 240 seconds. AWPS uses this constant by AWPS to alert personnel via the automatic voice/pager should confirmation of dome closure not occur.

13. Communications System

For the purposes of the SOA demonstration, the dial-on-demand communications suite performed satisfactorily. The technical solution allowed the rapid integration of the system without concern for the long lead times and high cost of dedicated leased lines. Although there were some problems during the demonstration with the routers "hanging up" after long periods of inactivity, one can easily address this by increasing the inactivity timeout parameter in the router configuration.

For a long-term demonstration or operational deployment of autonomous sites, the operational cost of the dial-on-demand solution would be significant. Therefore, for an operational deployment, a leased line is recommended if pre-existing network connectivity is not available. We recommend a Network Encryption System for deployments where pre-existing network connectivity is available, augmented by dial-on-demand if the system is critical to operational readiness.

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9 Reference e-mail sent from Mr. Robert Morris to Mr. John Africano and Mr. Paul Kervin on 20 Feb 97 titled Analysis of Raven Data

10 Reference Wallace, S., Sabol, C., "Use of the Raven Optical Sensor for Deep Space Orbit Determination," AAS/AIAA Astrodynamics Specialist Conference, Sun Valley, Idaho, August 4-7, 1997, AAS 97-705

14. Security Considerations

Although the SOA demonstration was autonomous, many questions remain concerning the operational implementation of unattended space surveillance sensors. Specifically, maintaining adequate data and physical security pose a significant challenge at unmanned sites. Potentially, one could deploy a system with integrated strongboxes and alarm systems for cryptographic equipment. Another alternative is to deploy only at locations where manned security already exists.

15. RED vs. YELLOW vs. GREEN Ops Status

We based the codes reported by SOA to the ODSP on a predicted performance of the system. Therefore, we made the decision to define red weather as those periods where the number of detected stars in the field of view was less than 5. Subsequent analysis indicates that a more meaningful number would have been around 12. Consequently, some of the data sent to the surrogate as U codes should legitimately been classified as W codes. This had dramatic consequences during night 219, for example. During the last 4 hours of the night, the dome malfunctioned, so that the dome obscured the stars. During this period, SOA sent 84 W codes and 36 U codes to the surrogate. It is obvious that, with the proper definition of red weather, all of those codes should have been W codes. This is true in general: the U codes define either red weather or red equipment. The large number of U codes sent to the surrogate is an artifact of the way the data was processed, not a true reflection of the system performance. If we treat the U codes as indicative of green conditions, the following becomes the number of hours of green time for each night.

Day	Green time (hrs)
209	3.3
210	7.4
212	3.7
213	7.3
216	3.6
217	7.3
218	7.6
219	4.9
224	5.8
225	5.8

Table 7 Green Time per Day

As noted above, if we compare the data for night 219 shown in the above table to the detailed data for that night, the artificial nature of this approach becomes obvious.

The following table indicates the performance, broken down by day, of the SOA system running autonomously during the 18-day period. For each day, the data of interest is:

- the "Green time", that is, the time the system was up and running in green weather and with no equipment problems
- the number of satellites for which observations were attempted
- the average throughput for satellite attempts
- the number of satellite tracks (4 or more observations/track) which were sent to the ODSP.

Day	Green time (hrs)	Attempts	Throughput (#/hr)	Tasked Acqs	Addl Acqs	Total Tracks
209	2.74	109	33	66	47	113
210	6.64	249	34	141	28	169
212	3.15	119	32	64	12	76
213	6.62	254	35	154	38	192
216	3.08	111	31	62	17	79
217	6.17	206	28	76	19	95
218	6.55	257	34	96	14	110
219	3.32	157	32	23	1	24
224	5.27	91	33	74	21	95
225	5.4	233	40	98	14	112
Total	49.14	1886	33	854	211	1065

TABLE 8 Testing Summary during Green Time

A random check of the additional acquisitions that SOA reported to the ODSP indicated that all of the additional acquisitions were on the tasking list for that night, so it is appropriate to take credit for those tracks.

In addition, there were a number of periods of yellow weather. SOA defines Yellow weather on an hourly basis. Yellow weather hours are those hours where a significant number of images have fewer than 80%-matched stars. The primary difference between green and yellow conditions is that, not surprisingly, the number of tracks goes down significantly compared to the number of attempts.

Day	Yellow time (hrs)	Attempts	Throughput (#/hr)	Tasked Acqs	Addl Acqs	Total Tracks
223	5.02	190	31	56	11	67
224	0.24	26	30	0	0	0
225	0.54	22	24	4	0	4
226	2.55	101	30	31	8	39
Tot	8.50	339	30	91	19	110

TABLE 9 Testing Summary during Yellow Time

The determination of what time was "yellow" weather is a more subjective issue. This is not only true of this demonstration, but is also true for the human operators at all three GEODSS sites, as well as the MSSS site. There is a great deal of judgment involved in when to call the weather yellow. The operator goes outside, looks at the sky, determines the cloud cover, determines which areas of the sky are clear and which are not, and arrives at a decision. Different operators will usually come up with different thresholds. For this discussion, the metric we used was to look at the Catalog Star Match Percentage (refer to the plots in a later section). This is the number of cataloged stars that SOA detected in the image, compared to the number that should have been in the image, expressed as a percentage. When there is high cirrus, for example, not all stars will be visible. For the purposes of this report, the weather was determined to be yellow if a significant number of images had match percentages lower than 80%. SOA performed this analysis on an hourly basis.

D. Implementation Cost Estimates

1. Independent Cost Estimate

One of the innovative advantages of the SOA concept is low implementation and operations cost. The Space Battlelab obtained an independent cost estimate from Aerospace Corporation (see Table 10) to aid HQ AFSPC in their decision making process. The Aerospace Corporation provides independent cost estimates for AFMC/SMC acquisitions. After review of the Aerospace data and discussions with AFMC/ESC and AFSPC/DRC we estimate that \$5 – 7 million would be sufficient to acquire, deploy and integrate three systems into the SSN. The annual operations and maintenance (O&M) cost for three sites would be ~\$800,000.

Aerospace assumed an independent contractor would acquire a SOA system from scratch, without the benefit of lessons-learned for the Space Battlelab demonstration. The availability of this report, AFRL personnel, and AFRL software for future reference should reduce the program development risk and make this a conservative cost estimate. Aerospace also estimated the recurring system acquisition cost and annual O&M cost. Aerospace did not include any System Program Office (SPO) overhead cost in the figures, estimated as an additional 20 – 25% of the program cost.

One item not included in the cost estimate is integration with the OC^3F. The current OC^3F cannot handle non-GEODSS standard telescopes, including TOS. The cost to modify the OC^3F for non-standard telescopes is ~\$1million. The recurring cost would be approximately \$100,000. These are Rough Order of Magnitude (ROM) costs from discussions with AFMC/ESC and their OC^3F development contractor, PRC.

			FY 98 Cost ($K)		
	Scratch	Scratch			
	FOB CONUS	FOB CONUS	Italy	Australia	Basis of Estimate
	1/2 deg FOV	1 deg FOV			
SYSTEM ACQUISITION	Non tracking mount	Tracking mount			
PMP Hardware					
* **Commercial Telescope (16")**	**17.0**	**100.0**	**100.0**	**17.0**	**Vendor quotes**
PC for Telescope Control	3.0	3.0	3.0	3.0	Vendor quotes
Data Processing Workstation	30.0	30.0	30.0	30.0	Vendor quotes
* **Charged Coupled Device (CCD) Camera**	**15.0**	**30.0**	**30.0**	**15.0**	**Vendor quotes**
GPS Receiver	3.0	3.0	3.0	3.0	Vendor quotes
STU III Encrypt/Decrypt Equipment	2.0	2.0	2.0	2.0	Vendor quotes
Professional Telescope Control Equip	11.0	11.0	11.0	11.0	plus assembly cost
Commercial ASH-DOME	14.2	14.2	14.2	14.2	plus shipping and assembly
Weather System Hardware	10.0	10.0	10.0	10.0	MIT/LL Analogy
Sub-total COTS HW	105.2	203.2	203.2	105.2	
Shipping	0.0	0.0	28.4	16.8	%HW (Italy /14%) / (Aust /16%)
Assembly/Travel (Prof Telscope)	5.0	5.0	9.0	9.8	Vendor data & area factor
Assembly/Travel (Comm ASH-DOME)	5.0	5.0	9.0	9.8	Vendor data & area factor
DEV/GOTS Software					
DEV/GOTS Processing S/W	810.0	810.0	0.0	0.0	16.2 KSLOC @ $50/LOC
COTS Telescope/Dome/CCD Control	3.0	3.0	3.0	3.0	Vendor quotes
GOTS (OC3F) Scheduler Mods	**0.0**	**0.0**	**0.0**	**0.0**	**Educated Guess**
PMP Software (Dev Only)					
Automated Weather Control	75.0	75.0	0.0	0.0	1KSLOC @ $75/LOC
Sub-total Software	888.0	888.0	252.6	144.6	
PMP IA&T	49.7	54.6	57.0	51.6	5% of all H/W & S/W
Prime Mission Product (PMP)	1042.9	1145.8	309.7	196.3	Sum
Initial Spares	10.5	20.3	20.3	10.5	5-20% cost hardware
Common Support Equipment	5.3	10.2	10.2	5.3	50% initial spares
Facilities	0.0	0.0	3.6	0.0	Dome Pad in Italy
SECRET Facility	0.0	0.0	30.0	30.0	100 ft2 @ $300/ft
Site Activation	0.0	0.0	21.7	13.7	7% PMP & Area Factor
Training	20.9	22.9	6.2	3.9	2-4% PMP
System Integration	83.4	91.7	24.8	15.7	8-10% PMP
System Program Level					
System Engineering	104.3	114.6	31.0	19.6	5-10% PMP
Program Management	104.3	114.6	31.0	19.6	10% PMP
System Test & Evaluation	52.1	57.3	15.5	9.8	
					5-15% PMP
System Data	62.6	68.7	18.6	11.8	6-10% PMP
TOTAL SYSTEM ACQUISITION	**1486.2**	**1646.0**	**522.4**	**336.3**	
G&A	n/a	n/a	n/a	n/a	7-15% of subtotal
Fee	n/a	n/a	n/a	n/a	10-12% of subtotal + G&A
OGC	n/a	n/a	n/a	n/a	4-12% of acq costs
TOTAL					
OPERATIONS & MAINTENANCE					
Mission Personnel (Staffing)					
Officers	0.0	0.0	0.0	0.0	$90K/person (0)
Enlisted	0.0	0.0	0.0	0.0	$45K/person (0)
Contractor	20.0	20.0	60.0	60.0	$160K/person (1) w/ travel
Program Mgt	40.0	40.0	0.0	0.0	$160K/person (1) w/ travel
Depot Maintenance	0.0	0.0	0.0	0.0	1-3% PMP Development H/W
Hardware (DEV)	0.0	0.0	0.0	0.0	5-15% Dev HW
Hardware (COTS)	21.0	40.6	21.0	21.0	20-33% of COTS
Software (COTS)	7.5	7.5	7.5	7.5	10-15% PMP SW
Software (DEV)	97.6	97.6	0.0	0.0	12-15% DEV SW
Sustaining Engineering	52.1	57.3	15.5	9.8	5% PMP
Modifications	20.9	22.9	6.2	3.9	2% PMP
Logistics	31.3	34.4	9.3	5.9	3-5% PMP
Facilities	0.0	0.0	0.4	0.0	10% Facilities (Acq)
Electricity	0.0	0.0	1.0	0.9	ROM
Backup Power	0.0	0.0	2.0	1.8	ROM
HVAC	0.0	0.0	1.0	0.9	ROM
Maintenance Contract	0.0	0.0	5.0	4.6	ROM
Security	0.0	0.0	2.4	2.4	ROM
Leased Lines	0.0	0.0	50.0	50.0	Based on TOS
Total O & M (Annual)	290.4	320.3	181.3	168.7	
					swc^soa1.xls

TABLE 10 Aerospace Cost Estimate

In Table 10 the first column is a description of the elements considered in the cost estimate.

The second cost column assumes the acquisition and deployment of the basic SOA system to Edwards AFB. It has $0.00 for the Facilities, SECRET Facilities, and Site Activation because the 18 SPSS is an existing facility that would provide services. The O&M cost does not include any Leased Line cost because the 18 SPSS would provide communications. The O&M budget includes the overhead of a "primary" site that provides system upgrades for remote site installation.

The third column shows an upgraded SOA system that includes a 1-degree field-of-view telescope with a tracking mount. Although this doubles the total hardware cost, the total cost increases by only ten percent.

The fourth column is the recurring cost for a site in Italy with an upgraded SOA system. We assumed TDY personnel would provide maintenance on an as-needed basis (approximately every 60 days). Note that the Software (DEV) cost is $0.0 and the greatly reduced Sustaining Engineering cost from the "primary" site.

The fifth column is the recurring site cost for Australia (consistent with the SOA demonstration) with a 1/2 degree FOV telescope.

The last column is the basis of estimate.

2. Operational Cost Comparison

One of the essential drivers in a decision to acquire a system is the long term O&M cost. The advantages of the SOA concept with COTS based hardware and software, and un-manned operations are clear.

	Objects / site	O&M cost / object	Operators/ site
Baseline GEODSS	~125	$38	9
Refurbished GEODSS (POMed for Sustainment)	~450	$15	9
SOA (3 telescopes) $5-7M	~450	$6	0

TABLE 11 Long Term O&M Cost Comparison

As can be seen in Table 11, the AFSPC GEODSS refurbishment effort of ~$60million will have significant long term O&M cost impacts. However, the O&M cost per object for the SOA concept is 2.5 times less than the refurbished GEODSS. The SOA concept is clearly a cost-effective investment.

4. CONCLUSION

A. Deployment

HQ AFSPC should address the SSN coverage and capacity limitations for deep space objects. Too many objects receive inadequate tracking and the problem will only get worse as the number of objects on-orbit increases. Therefore, the Space Battlelab believes that HQ AFSPC should, at a minimum, acquire three upgraded SOA systems with a 1-degree FOV telescopes and tracking mounts.

HQ AFSPC should deploy the three systems to ensure redundant coverage of deep space as shown in Figure 33. The site in Australia would cover the gap in Australia and provide partially overlapping coverage for Diego Garcia. The European site would provide overlapping coverage for TOS in Moron, Spain and provide partially overlapping coverage for Diego Garcia. The site in Southwest Asia would provide significant overlap for both Moron, Spain and Diego Garcia.

In addition to the coverage improvements, the SSN capacity would also improve as shown in Figure 34. Although the total capacity shortfall still exists, three-telescope augmentation should allow the SSN to meet the GEODSS ORD requirement to track all deep space objects once every three days. In addition, SOA should significantly reduce the number of objects on the attention list and lost list.

B. System Configuration

In general, the system configuration used for the SOA demonstration was successful. However, several minor design implementation issues discussed in the report (i.e. communications approach) are appropriate for a SPO to consider when acquiring the system. The Space Battlelab did not intend the demonstration to define fully all requirements for an operational system.

There are two hardware changes identified during the demonstration that would substantially improve the system performance: expand the telescope FOV and minimize the telescope mount limitations. (1) A wider FOV telescope would increase the number of objects visible to the system as discussed in section 3C4, Minimum and Maximum Tracking Rates, and allow the SOA system more effectively augment the SSN. (2) The telescope mount was a major driver in the system performance in both throughput and acquisition rate. As discussed in section 3C2, Throughput, a mount that does not have meridian crossing limitations would simplify OC^{3}F tasking and improve system performance. In addition, the mount should have the ability to track an object to allow the system to operate in a rate-track mode. The acquisition rate for the system increased when in rate-track mode as described in section 3C5D, Satellite Category.

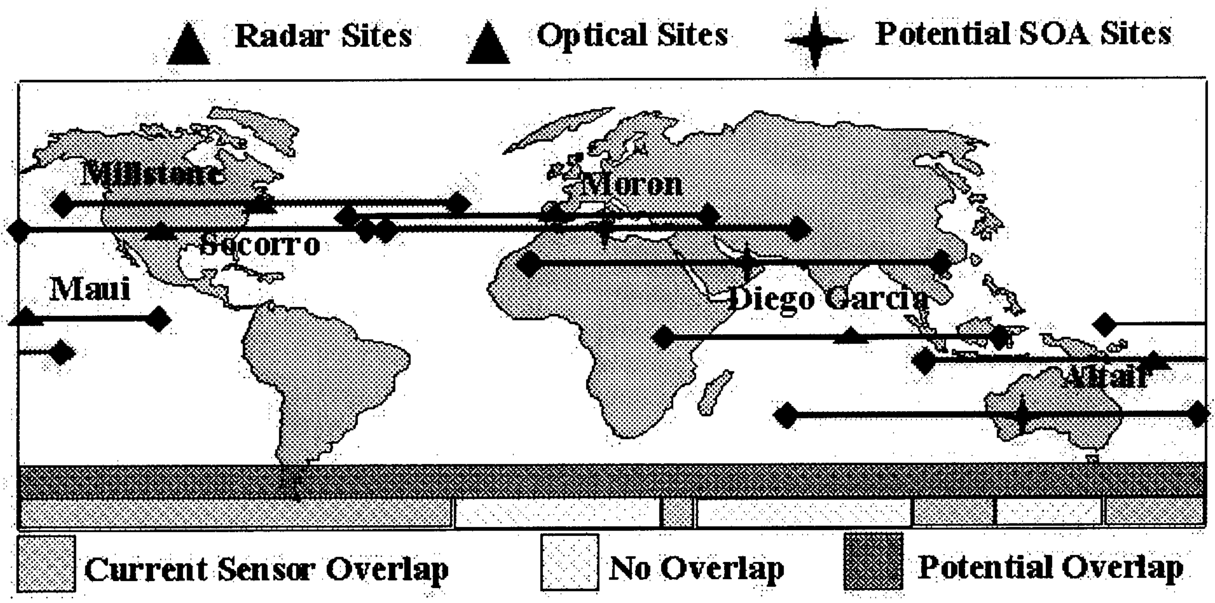

Figure 33 SSN DS Coverage with 3 SOA Systems

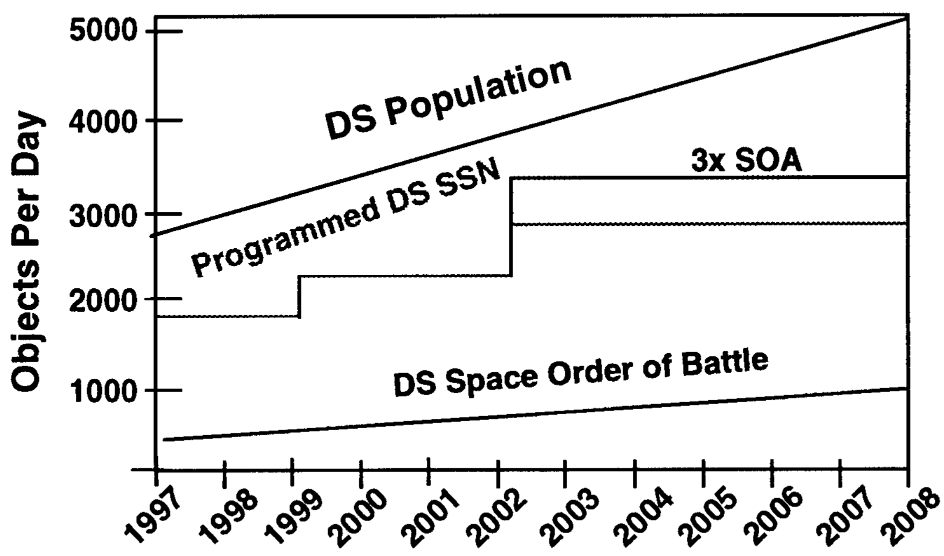

Figure 34 Capacity Shortfalls with 3 SOA Systems

5. ACKNOWLEDGEMENTS

The lack of validated requirements and specifications and the rapid nature of the Battlelab demonstration process require flexibility on the part of all players. The Space Battlelab's first demonstration was successful because of the hard work and dedication provided by AFRL, MIT/LL, and 18 SPSS personnel.